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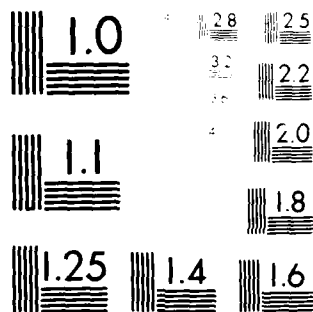
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ENERGY POLICIES FOR RESILIENCE AND NATIONAL SECURITY

LEVEL *II*

Final Report to the
Council on Environmental Quality
Executive Office of the President
Washington, D.C. 20006

under Contract #EQ9AC016

by

Amory B. Lovins and L. Hunter Lovins
→ Friends of the Earth, Inc.
124 Spear Street, San Francisco, California 94105

October 1981

for the Federal Emergency Management Agency
Washington, D.C. 20472

under Contract DCPA-01-79-C-0317
FEMA Work Unit 4351C
Program Manager: Mr. George Divine, FEMA

FEMA Review Notice

This report has been reviewed in the Federal Emergency Management Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Federal Emergency Management Agency.

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ENERGY POLICIES FOR RESILIENCE AND NATIONAL SECURITY

Final Report (October 1981) for the Federal Emergency Management Agency (Work Unit 4351C) by Amory B. Lovins and L. Hunter Lovins* under Contract DCPA 01-79-C-0317

Detachable Summary

The U.S. energy system is highly vulnerable to large-scale failures with catastrophic consequences, and is becoming more so. This study analyzes the origins of that vulnerability, both generically and specifically. We conclude that America's energy insecurity stems from the nature, organization, control structure, and interconnections of highly centralized technologies. These technologies--which unfortunately dominate both the present energy system and current national policy--cannot withstand terrorism, sabotage, enemy attack, natural disaster, or even accidental technical failure. The resulting brittleness of energy supplies poses a grave and growing threat to national security, life, and liberty. It also frustrates the efforts of our Armed Forces to defend a country whose energy supplies can be turned off by a handful of people.

Energy is more than oil, and energy security is more than ability to keep the oil coming. Although current inability to guarantee oil supplies is a serious problem, previous analyses of energy security have focused all but exclusively on oil, and have therefore diverted attention from a more comprehensive understanding of how to achieve energy security. Since, moreover, Federal energy planning does not consider vulnerability as a criterion, many policies proposed to reduce dependence on imported oil are actually making energy supplies more vulnerable in other and even less tractable ways. Conversely, opportunities for simultaneously reducing oil dependence and other energy vulnerabilities are being ignored.

This analysis, addressed to a general policy audience with basic numeracy, and to energy and preparedness professionals, seeks systematically to identify and apply those design principles that can make America's energy system more resilient, less vulnerable, less susceptible to catastrophic failures: in short, to make the nation better prepared for all kinds of disruptions, whether civil or military, foreseen or unforeseen. This study shows why traditional measures designed merely to make energy supplies more reliable in the face of calculable, predictable kinds of technical failure cannot achieve such basic resilience and may even reduce it. In contrast, by drawing on such areas of design as biology, telecommunications, data processing, nuclear engineering, and aeronautics, we identify practical design elements, technologies, and principles of system architecture which can make catastrophic failures structurally impossible.

The most cost-effective approach embodying these principles is to increase dramatically the efficiency of using energy. This displaces the most insecure marginal supplies, stretches time constants, shaves peak loads, limits extremes of system behavior, and greatly increases the scope for improvised supplies. The next priority is to harness a wide range of presently available, relatively dispersed, renewable sources whose scale, location, and energy quality are appropriate to their task. In combination, and with due attention to some currently ignored details of design, technologies for high energy productivity and appropriate renewable supply would provide an inherently resilient energy system, with profound benefits for individual and national security.

It is thus encouraging that these two types of measures are today respectively the cheapest and second-cheapest, and the fastest-growing and second-fastest-growing, contributors to national energy supply. They would spread even faster in a truly competitive marketplace or with greater reliance on individual and community initiative (some grassroots efforts to mobilize such resilient technologies are already underway). This analysis thus concludes that an energy policy consistent with free-market principles can provide lasting energy security for a free society--if the foundations of that security are clearly understood.

*FOE, 124 Spear St., San Francisco CA 94105

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This study was suggested by Mr. Bardyl Tirana, then Director of the Defense Civil Preparedness Agency, U.S. Department of Defense, following a seminar which Mr. Tirana and Dr. Frank Kapper kindly arranged for the Project Leader to give for Service energy directors and others in the Office of the Joint Chiefs of Staff. We are grateful to Mr. Tirana for taking time from reorganizing DCPA and other components into the Federal Emergency Management Agency (FEMA) to give this work its initial impetus. We appreciate equally the thoughtful guidance, help, and encouragement we have since received from our two program managers, Mr. George Divine of FEMA and Mr. John Davidson of CEQ.

Much of the labor of gathering and sifting several cubic meters of paper was most ably and cheerfully done by our research assistant, a Yale psychology graduate, Mr. Gabriel Gorenstein. Our efforts to frame the problem, and many logistical arrangements, were greatly aided by our colleagues Mr. Jim Harding and Jeff Knight, Esq., respectively serving with the International Project for Soft Energy Paths and its sponsoring organization, Friends of the Earth Foundation. Ms. Cissy Wallace, Mr. John Fore, and Ms. Katy Slichter served faithfully as our IPSEP liaisons, handling our papers and voluminous mail.

For the intellectual content of this study we are alone responsible, but we have benefited enormously from interchange with others. Among the most valuable contributors, voluntary or unknowing, have been Dr. Jan Beyea, Capt. Howard Bucknell III (USN Ret.) and his colleagues at the Energy and National Security Project at The Merston Center of Ohio State University (the site of another seminar), Mr. Wilson Clark, Dr. Ruthann Corwin, Dr. Paul Craig, Mr. F.R. Farmer and his colleagues in the nuclear industry who generously shared their insights into the principles of resilient design, Dr. Karl Gawell, Dr. Jim Gray, Mr. Bruce Green, Mr. Patrick Heffernan, Ms. Tina Hobson, Prof. John Holdren, Prof. C.S. Holling (to whom we owe the whole concept of resilience), Col. William Holmberg (USMC Ret.), Dr. Paul Hoover (also at Merston), Mr. Alec Jenkins, Dr. Edward Kahn, Mr. Fran Koster, Dr. Florentin Krause, Dr. Enver Masud, Dr. Bud Miles, the National Defense University (another seminar venue), The RAND Corporation, Dr. Bent Sørensen, Dr. Peter Steen and the Swedish Defense Research Establishment (FOA), Dr. David Sternlight and the Atlantic Richfield Company, Commissioner Gene Varinini, and dozens of other colleagues whose concepts and data have enriched us over the years.

The draft of this manuscript was submitted to FEMA at the beginning of June 1981 and sent concurrently to about sixty expert reviewers in civilian and military agencies, private industry, foundations, universities, and consulting firms. We are most grateful to the more than twenty who took time out of their busy schedules to offer constructive comments, most of which are reflected in this final draft. These reviewers include many mentioned above, plus Dr. Melvin Conant, Mr. Peter Gleick, Prof. Barry Hyman, Mr. H. Richard Holt, Dr. David Morris, Mr. John R. Newell, and Dr. Zdanek Zofka. No reviewers, of course, share any of our responsibility for the result.

Most of all we are grateful to Mrs. Farley Sheldon for her tolerant hospitality, and to Mr. Chris Cappy for his frequent help, during the throes of our writing.

--Amory B. and L. Hunter Lovins

Los Angeles
28 October 1981

About the Authors

Amory B. Lovins, the Project Leader in this study, is a consultant physicist, born in Washington, D.C. in 1947. After two years each at Harvard College and at Magdalen College, Oxford, he became a Junior Research Fellow at Merton College, Oxford in 1969, but resigned in 1971 to work full-time from a London base (returning to the United States in 1981) for Friends of the Earth, Inc., a U.S. non-profit conservation group. He received an Oxford M.A. degree by Special Resolution in 1971 and D.Sc. degrees honoris causa from Bates College in 1979 and Williams College in 1981. Twice Regents' Lecturer in the University of California (Berkeley, energy policy, 1978, and Riverside, economics, 1980), he was 1979 Grauer Lecturer in the University of British Columbia. In 1980-81 he served on the Energy Research Advisory Board of the U.S. Department of Energy.

Mr. Lovins's experimental physics consultancy (1965-) shifted to energy and resource strategy in the early 1970s. His current or recent clients, none of whom is responsible for his views, include several United Nations agencies, the Organization for Economic Cooperation and Development (OECD), the International Federation of Institutes for Advanced Studies (IFIAS), the MIT Workshop on Alternative Energy Strategies (WAES), the Science Council of Canada, Petro-Canada, the U.S. Department of Energy, the U.S. Congress's Office of Technology Assessment, the U.S. Solar Energy Research Institute, Resources for the Future, and various state and foreign governments and financial institutions. He has published nine books (of which six deal with energy policy) and numerous technical papers. In 1979 he married L. Hunter Sheldon, Esq. They now work as a team on energy policy in about fifteen countries, and as joint Policy Advisors to FOE. In spring 1982 they will serve as Luce Visiting Professors of Environmental Studies at Dartmouth College, and in summer 1982 as Distinguished Visiting Professors in the University of Colorado at Boulder.

L. Hunter Lovins, Co-Investigator in this study, is a lawyer, political scientist, sociologist, and forester. She was born in Vermont in 1950. Her 1971 B.A. degree from Pitzer College was a double major in political studies and sociology; her law degree (J.D.) from Loyola University School of Law (Los Angeles), accompanied by the Alumni Award for Outstanding Service, concentrated on land use, administrative, and environmental law. Since 1975 she has been a member of the California Bar and a partner of Hirschtick & Sheldon, Los Angeles.

From 1974 to 1979 Ms. Lovins served as Assistant Director of the California Conservation Project ("Tree People"), which she helped to establish in Los Angeles. She designed and implemented the Project's energy and environmental education projects, coordinated community participation in urban forestry, and served as photographer, firefighter, and emergency logistics and disaster-relief coordinator. She has lectured and consulted widely on energy and environmental education, community organizing, urban forestry, and biomass energy; co-instructed energy workshops for the University of Oklahoma, Dartmouth College, the American Association for the Advancement of Science, and others; served in 1979 on the City of Los Angeles Energy Management Board; and co-authored and edited recent publications with her husband, including the Summer 1980 Foreign Affairs article "Nuclear Power and Nuclear Bombs", its expansion Energy/War: Breaking the Nuclear Link, and Least-Cost Energy: Solving the CO₂ Problem, originally a study for the West German government.

The International Project for Soft Energy Paths (IPSEP) is a non-profit research and educational project. Its bimonthly journal Soft Energy Notes, circulated in over eighty countries and reprinted by the U.S. Department of Energy, is a basic source of up-to-date technical, economic, analytic, and institutional information on efficient, renewable-based energy strategies. IPSEP, a project of FOE Foundation (of which Mr. Lovins is Vice President), was established in 1978 with support from the Max and Anna Levinson Foundation, and is currently financed by subscriptions, grants, and consulting contracts. It welcomes inquiries and technical or financial contributions.

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PREFACE: PURPOSE, METHOD, AND SCOPE

The first comprehensive oversight examination of Federal efforts towards nonmilitary emergency preparedness opened its report [Joint Committee on Defense Production 1977:I-vii]* with this finding:

An increasingly complex, technology-dependent, industrial economy in the United States has made citizens more than ever vulnerable to the effects of disasters and emergencies over which they have little or no control and to which they cannot successfully respond as individuals.

Most modern systems for supplying energy carry in their design the seeds of this brittleness: complexity of components and structure; highly interactive and poorly understood system behavior; likelihood of unexpected, unpredictable disturbances; difficulty of diagnosing, repairing, and replacing disabled parts; proneness both to exacerbate and to be disrupted by sociopolitical tensions and instabilities; potential for sudden failure on a massive scale; and profound importance for well-being, social cohesiveness, and national survival.

Our nation has invested enormous resources in military measures to deter and defeat aggression, and to project U.S. power abroad to guard perceived national interests. Yet at the same time, we have made both this military might and every facet of our civilian life dependent on an energy system inherently vulnerable to large-scale failure, whether caused by accident or by malice. We have developed a society, for example, in which the basic functions of life depend on a continuous supply of electricity. In New York City, traveling, going upstairs, opening doors, even walking, eating, seeing, and breathing often depend on the electrical supply. Just a brief faltering of such services as electricity, gas, food, water, and sewage treatment can manifest--sometimes fatally--the latent brittleness of our interdependent, urbanized society. Yet the systems that provide these services seem increasingly to be so ordered as to magnify, even perhaps to maximize, that vulnerability.

Our electrical systems, for example, depend on many large and precise machines, rotating in exact synchrony across a continent, and strung together by an easily severed network of aerial arteries. Electricity cannot be readily stored in bulk, so failure is instantly disruptive. Failure also becomes more damaging and less tractable on a large scale. The very size and complexity of

*Throughout this report, bracketed citations refer by author and date, and if needed by volume and page number (after the colon), to consolidated references listed alphabetically starting on page 280. Occasional omissions of citations are generally to protect a specific point of vulnerability from being identified or to honor a source's wish that a statement not be attributed.

modern power grids, their reliance on elaborate control and communications systems, even the inherent electrical properties of long transmission lines, tend to increase the likelihood and consequences of major failures. There "is little doubt" that a few high-altitude nuclear blasts, perhaps even one, "could black out all U.S. power grids" [Lerner 1981:43]. Even more strikingly, we have now reached the point where a handful of people with rifles may be able to turn off virtually the whole country. Such homemade threats to our national security appear to undermine the mission of our Armed Forces, and would be a grave preparedness problem even if our nation had no adversaries in the world.

This study explores in detail the validity of such concepts as a linkage between energy vulnerability and central electrification. By exploring those technological and architectural features which make the energy system brittle, the analysis seeks to identify and reduce to specific, practical form those design principles that can make our energy system more resilient, less vulnerable, less susceptible to catastrophic failures: in short, better prepared for all kinds of disruptions, whether civil or military, foreseen or unforeseen.

The motivation for tackling this difficult, seemingly amorphous subject is the unpleasant discovery, on reviewing the open literature, that:

- Comparative vulnerability has been analyzed only in a very narrow sense. There is no conceptual framework for assessing vulnerability to a full range of potential disturbances. Many existing methodologies are misleading, because

- Most analytic and design efforts seek reliability against calculable technical failures, but this does not impart, and may even reduce, resilience against incalculable or unexpected disruptions, especially deliberate ones.

- Comparative vulnerability is seldom even considered as a criterion in Federal energy policy decisions, whether by the Congress or the Executive.

- Technologies and system designs that offer the greatest potential improvements in preparedness (together with other important advantages) generally have been least analyzed, and have lowest priority in current Federal policy.

- Most trends in Federal energy policy appear to be increasing vulnerability, often in the name of reducing it: specifically, many of the systems proposed to displace imported oil are themselves subject to other and arguably graver security drawbacks.

- Preparedness policies, though growing beyond their traditional emphasis on the threat of nuclear attack, remain inadequate to mitigate threats posed by the increasing structural vulnerability of the U.S. energy system.

- In particular, although energy preparedness analyses and policies have been almost completely directed towards coping with reductions or interruptions of oil imports, many other forms of energy vulnerability--less obvious but perhaps even more dangerous--have been largely neglected.

These other, wider vulnerabilities form the main (though not the exclusive) focus of this study. The Secretary of Defense's statement [Brown 1977] that "there is no more serious threat to the long-term security of the United States and to its allies than that which stems from the growing deficiency of secure and assured energy resources..." is true in a far broader sense than he presumably intended; and this study seeks systematically to explicate that sense.

The oil problem is real, difficult, and urgent. Even if oil reserves were unlimited, their proprietors permanently friendly and reliable, and their delivery systems permanently secure from interference, there would be serious national-security problems just from the enormity of our oil import bill. During 1979-80, while U.S. oil imports fell by about 20%, their cost rose by nearly 50% to almost \$90 billion--equivalent, as John Sawhill put it, to the total net assets of General Motors, Ford, IBM, and General Electric, or to nearly 40% of all U.S. exports. But in fact, oil reserves and resources are limited; many of their main proprietors are neither friendly nor reliable; much of the supply line stretches halfway around the world; and "every main oil loading port in the Persian Gulf and most of the Saudi Arabian and the United Arab Emirates oil fields are within 900 miles (a 90-minute subsonic flight) of the Soviet Union" (and closer still to Soviet facilities in Afghanistan and elsewhere) [U.S. General Accounting Office 1979:3]. "In the event of some future confrontation, the Soviet Union might be able to restrict access of the Western World to its essential oil supplies to a degree of severity and duration greater than any embargo by the oil producers....[A]ction to interdict on the high seas tanker movement of oil...could vastly exacerbate the oil supply situation...."[Brown 1980]

There is a consensus that despite much effort, oil vulnerabilities remain unacceptably large [Emergency Preparedness News 1980; Deese & Nye 1981; Yorke 1980; Alm 1981; Marshall 1980; Senate Committee on Energy & Natural Resources 1980; Aspen Institute 1980]. Our thesis, however, is that energy is far more than oil, and energy security is far more than ability to keep the oil coming. Thus even if the oil problem is solved, major and unexamined energy vulnerabilities will remain. Many measures being used to "solve" the oil problem will indeed make those other vulnerabilities worse. Other measures not now being implemented could probably provide both greater relief of oil dependence and more comprehensive energy security. This report's emphasis on vulnerabilities other than imported oil, then, arises not from a lack of concern about the oil problem, but from an even deeper concern that the whole problem of energy preparedness has been misconceived. Though discussions with people professionally concerned with preparedness have consistently elicited intense interest in

this thesis, the urgency of the oil problem has so confined analysts' attention that there is virtually no literature directly bearing on these concerns. With the exception of one project now underway at FOA (the Swedish Defense Research Establishment), there appears to be no comparable analysis anywhere in the world. Our investigations also revealed that although some individual analysts in the Department of Energy think about pieces of the vulnerability problem, the Department as an institution has not yet seriously considered the broader preparedness implications or the inherent vulnerabilities of energy systems being promoted on other grounds. This report seeks to begin to fill that broad and important gap, even if in a preliminary fashion that can doubtless be refined by those with greater knowledge and resources.

The Federal Emergency Management Agency has already sponsored a parallel study [Energy & Defense Project 1980], carried out independently of this one, which might at first sight appear to have covered its concerns. That work is helpful and relevant but largely complementary to the line of this analysis. It offers an opportunity to avoid possible overlap by simply citing much of its material--notably its readable exposition of the status of various renewable energy sources--but this report aims at considerably deeper conceptual analysis of energy vulnerability and resilience. Both studies seek to address FEMA's need to find out more about emerging technologies and energy-system design principles that can enhance preparedness, and to alert FEMA to actions that may be needed to ensure adequate attention to preparedness in formulating energy policy. (Much of this study should also help FEMA in its counter-terrorism consequence preparedness planning.) But where the Energy and Defense Project's efforts are directed more towards a survey of available technologies, this analysis, while including ample technological material, will also seek to systematize in far greater detail some design principles for energy resilience.

This study is of necessity exploratory and conceptual. Because the problem as framed here has not been systematically studied, it has been necessary to synthesize ideas from an extensive survey of many diverse literatures (some in subjects not normally considered in research of this kind) and from dozens of interviews and letters, together with a good deal of hard thinking. The present treatment uses quantitative expression where it will illuminate rather than obscure qualitative insights, but avoids opaquely elaborate computer models of concepts better kept in words: much of the argument simply does not lend itself to formal modelling so much as to analogy and anecdote. Some sections require modest technical background to follow in detail, but most are written for a general policy audience with basic numeracy. References are also supplied to enable specialists to dig deeper if they wish.

To do justice to the richness of the concepts of vulnerability and resilience, and to organize systematically a large mass of supporting examples, it proved necessary to rearrange the sequence of topics originally envisaged in the contractual Statement of Work, developing the same subjects in an order better suited to the intellectual structure of the argument. For the reader's convenience, the following key shows how the topics in the Statement of Work (Clause 101. General Scope) correspond to sections of the text:

"1. Background

"(a) Conventional energy sources as well as the new emerging energy technologies pose substantial public risks both in normal operation and as targets for sabotage. The potential positive and negative events which may derive from traditional and new sources of energy have not been identified or analyzed.

"(b) Current civil preparedness policies may not be adequate in mitigating the possible adverse impacts of alternative energy technologies. The proposed research will include the following:

"2. Specific Work for Services

Chapter(s)

"The contractor shall...conduct an impact analysis of alternative energy technologies to include but not be limited to the following:

- | | |
|---|--|
| "(a) Identify and analyze the risks and benefits inherent to conventional energy technologies and their potential vulnerability to natural and man made disasters (including enemy attack) industrial accidents and sabotage. | 1-3 |
| "(b) Identify and analyze the risks and benefits of emerging renewable energy technologies and their potential vulnerability to natural and man made disasters (including enemy attack) industrial accidents and sabotage. | 2.1.8, 2.2.2-3, 6-7 |
| "(c) The[se] analyses...will include but not be limited to such factors as identification of fuel types, delivery methods, distance and risks of distribution networks, ease of storability, ease of operation and repair, and adaptability to alternative fuel sources and cost-effectiveness comparisons. | 2.1.5, 3.2, 3.3.1
2.1.4, 2.1.7, 3
2.1-2, 2.4, 3
2.1.4, 2.1.6, 3,
6.2-3, 7.1, 7.2.3
2.1.7, 2.2-3, 6.2-3, 7, 8
2.1.5, 4.4, 6.2-3, 7.3.2
5.2, 6.1, 6.4-5, 7.2.1, 7.3.1-2 |
| "(d) Identify and analyze the potential economic, social and political impacts of emerging, renewable energy sources. | 2.1.2-3, 2.1.10, 4.4, 6-8 |
| "(e) Review and discuss civil preparedness policies to determine their applicability and effectiveness in mitigating the possible adverse impacts of alternative energy technologies. Consideration will be given to the emerging set of policies associated with renewable energy technology." | 2.3, 3.4.4, 4.4, 5.2.10, 6.3, 7.2.3, 8 |

To ensure a coherent understanding of how these subjects interrelate, however, the reader is urged to study this report as a whole and in its proper order.

Any analysis of vulnerabilities must be carefully framed in order not to provide a manual for the malicious. Every effort has been made here to omit those concepts and technical details which would be useful to a saboteur with sufficient skill and insight to be effective in the first place: that is, the material presented is meant to be grossly insufficient to help persons who do not have such skill and superfluous to those who do.* Some residual risk will nonetheless remain--perhaps the price of free and informed discussion in a democracy. We believe the only thing more dangerous than discreetly discussing these distressing matters is not discussing them--hence leaving the real dangers to be enshrined in public policy and exploited by ingenious malevolence.

The boundaries of this analysis exclude, among other important topics, U.S. defense and military policy; most of the social, political, and psychological dimensions of preparedness [Dresch & Ellis 1966]; save in passing, vulnerabilities outside the sphere of energy policy; the detailed structure of U.S. institutions and policies for preparedness; and the detailed relevance of the thesis to U.S. allies or adversaries or to nonaligned (especially developing) countries. This report should not be viewed as a fundamental critique of U.S. energy policies on grounds other than their relevance to preparedness. It seeks to analyze how energy policy institutions should think about vulnerability rather than to specify how those thoughts should be embodied in institutional structure. Further, the 1981 change of Administration, the subsequent transition period, and the autumn 1981 proposal to abolish the Department of Energy complicate any description of Federal energy policy. While broad policy principles were enunciated in July 1981 [DOE 1981a], it is not yet clear how generalities will be specifically implemented nor how certain internal tensions will be resolved. Given such flux, this report can only describe synoptic trends for the next few years as the Federal energy role diminishes.

Finally, though we have extensive practical experience of local preparedness (organizing responses to storms, fires, etc.), we are not experts on preparedness in the sense in which many FEMA staff are. But from energy policy, our main field of professional activity, we hope to offer some insights which, while perhaps not in the accustomed language or mode of thinking of many preparedness studies, will be fresh and provocative. If this analysis stimulates more sophisticated successors which, in a few years, make this one look primitive by comparison, it will have succeeded in drawing attention to a grave and overlooked threat to both individual and national security.

*The authors are familiar with this problem through working with reviewers at the nuclear weapons laboratories to ensure discretion in certain unclassified technical papers, e.g. [Lovins 1980] (reprinted in Appendix B).

1. NATIONAL SECURITY AND PREPAREDNESS

1.1. Preparedness for what?

What is national security? The phrase "is at best an ambiguous symbol" and "tends to change...over time unless defined in terms of basic constructs." According to a Polaris submarine captain turned political scientist,

It is often used by Congress, the President, the Courts, or individuals or corporations to propose or to justify measures not supported by existing public perceptions. It is used only less sparingly than the phrase "in the national interest" which has a built-in attraction for the zealot, the scoundrel, and the patriot alike. [Bucknell 1979:2]

Despite overuse and perhaps abuse, the term "national security" speaks to important and legitimate concerns. Logically, the "basic constructs" defining it* should be such supreme interests as life, liberty, and the pursuit of happiness or of economic welfare. Derived from such overriding national interests or values--and from the principle that one ought never to have to choose between them--are corresponding goals, objectives, policies, and policy instruments. Thus, world peace might be a goal serving these values; a just peace in the Middle East might be an objective through which this goal can be realized; maintaining alliance structures, containing Communism, recognizing nations' right to live peacefully within their boundaries, or seeking autonomy for displaced peoples might be policies toward achieving that objective; and instruments of such policies might include diplomacy, foreign aid, war, trade and resource policy, etc. Military force, then, is only a means to serve higher ends [Nevins 1979]. But the traditional formulation of national security objectives, vintage pre-1965 or so, frames them as if both threats and responses were primarily military. A spectrum of such objectives could include:

- Maintaining stable, predictable international alignments and fostering sound, lasting alliances.
- Maintaining influence and confidence to mediate others' disputes peacefully rather than being drawn into them militarily.
- Seeking a comity between nations and peoples which will minimize the likelihood of resort to military means of settling disputes.
- Retaining in an interdependent world sufficient freedom of action to be able to conduct an independent foreign policy that does not require compromise between vital national interests.

*We consider here only concrete elements as opposed to perceptions of national security. Such observers as Lasswell [1977] argue that the latter are at least as important to the way people and nations behave.

- Achieving security from cutoff of vital supplies, such as oil [Collins & Mark 1979], food, and key minerals*.

- Inhibiting the vertical and horizontal spread and the refinement of nuclear weapons and other weapons of mass destruction.

- Reducing the likelihood and consequences of terrorism and surrogate war.

- Reducing the likelihood and consequences of direct military attack on the territory of the United States or of treaty allies.

The principal precondition for achieving these objectives, and for effective use of diplomacy, trade negotiations, and other non-military policy instruments, has long been considered to be military strength.

Military strength in turn requires reliable access to many resources. Of these, among the most important is energy in suitable forms to drive the engines of war. In World War II, the Allied loss of 550 oil tankers at sea was made up by the ability of U.S. industry--then fueled chiefly by coal--to build 908 more [Bucknell et al. 1979:16]. The coal was domestic; the diversity was crucial. In the Suez Crisis of 1956, U.S. oil surge capacity permitted the resupply of Europe. That flexibility has since disappeared.

Vietnam was America's first largely oil-fueled war, and its direct use of some 1.1-1.2 million barrels of oil per day--some 9% of total national oil consumption, or nearly twice the fraction lost in the 1973-74 Arab oil embargo [id.:18-20]--accelerated the rapid shift of the United States to being a net oil importer. Any future wars may have to be fought largely with oil procured from foreign countries and delivered in foreign vessels by foreign crews [id.: 21]. Fighting a replica of World War II today with 90% of our oil imports interdicted would require roughly half the nation's total oil consumption [id.:22], implying drastic civilian rationing if not worse, and accentuating

*Many of the energy issues considered in this study apply also to non-fuel minerals. Among the more useful introductions to this enormous field are [Fishman 1980; Broad 1980; Stanley 1977; Goodman 1978; Joint Committee on Defense Production 1977:I:87-97; Office of Technology Assessment 1979; Ayres & Narkus-Kramer 1976; Krause 1981; Kihlstedt 1977; Lovins 1973].

†Some analysts [Boston Study Group 1979] believe that because of geography, there is no significant military threat to the territory of the United States that can be defended against: apart from minor incursions handled by the Coast Guard, the only overt external risk is from strategic nuclear attack, which cannot be defended against, although it may be deterred. (A modest Poseidon fleet would do this: each of the 31 Poseidon submarines has 16 missiles, each capable of carrying 10-14 MIRVs--a total of 160-224 independently targetable warheads per submarine, or about one for each of the 218 Soviet cities of over 100,000 population. Each warhead has a nominal yield of about 40 kT--three Hiroshimas--and would kill roughly half the people in an area of the order of 15 square miles.) In this view, the United States itself could be adequately defended with some 3% of its present military budget, and the remainder is for general-purpose forces to defend U.S. allies and trade routes and to protect other U.S. interests abroad. Further pursuing such arguments, or the deterrence doctrine [Dyson 1981], is beyond the scope of this study.

the dangers of a protracted war of attrition against a country with relatively secure oil access [*id.*:23]. Indeed, this may underestimate the problem, since modern weapons require very highly refined fuels--a barrel of JP4 jet fuel needs about two barrels of crude oil [*id.*:25]--and present surge capacity and stockpiles are too limited for any but the briefest of wars. (DOD stockpiles in 1978 were about one month's peacetime use [Congressional Research Service 1978:44].) The serious problem of guaranteeing fuels for today's military establishment [Moreland 1979] naturally lends a sense of urgency to military assessments of energy security.

In recent years, however, it has become clear that these justified military concerns reflect in microcosm the role of energy in the vulnerability of the whole economy. "Of the most immediate concern" among "the main long-range trends that could threaten U.S. security," according to the 1978 DOD Annual Report [Brown 1978:26-27], is "the worldwide increase in the consumption of energy, and especially oil." The goal of mitigating that threat led to four "major objectives for U.S. energy policy" [*id.*]: providing "secure access to the energy necessary to maintain our standards of living and continue our economic growth," ensuring the same opportunities for our allies, avoiding excessive dependence on one type or source of energy, and keeping "the major sources of energy from falling into unfriendly hands. These conditions," concluded the Secretary, "are essential to U.S. security"--for only by meeting them "can we surmount the energy crisis. Only by surmounting the energy crisis can we retain the strength necessary to uphold U.S. security." But the stated objectives are to be pursued, not by increasing military strength, but by the familiar non-military means of national energy policy as a whole: expanding domestic reserves, diversification, substitution, conservation, and stockpiling [*id.*]

Further, a largely military approach to national security seems increasingly unresponsive to the interdependencies of a world in which the religious trends in Saudi Arabian society or the rate of decline of Romanian oil reserves can be as significant to U.S. oil supplies as Soviet expansionism. As General Maxwell D. Taylor [1976] remarked,

Most Americans have been accustomed to regard national security as something having to do with the military defense of the country against a military enemy, and this as a responsibility primarily of the armed forces To remove past ambiguities and recognize the widened spectrum of threats to our security, we should recognize that adequate protection in the future must embrace all important valuables, tangible or otherwise, in the form of assets, national interests, or sources of future strength.... An adequate national security policy must provide ample protection for the foregoing classes of valuables, wherever found, from dangers military and non-military, foreign and domestic, utilizing for the purpose all appropriate forms of national power.

Likewise, Moreland and Bucknell [1978:6] emphasize that

4

...national security in its total sense is not simply a matter of defending against external threats or becoming embroiled in wars abroad. The internal security of our country is properly a matter of national security concern. Because of the ubiquitous effects of energy supply and use in our society, it is apparent even now that major fuel shortages and a failure to undertake conservation and to develop alternative supplies in a timely manner could lead to severe conditions of depression, social unrest, violence, and political peril. Similarly, the threat of those dangers could cause us to undertake wars for which we are ill-prepared.

In response to wider threats, a correspondingly broadened concept of preparedness has evolved [Joint Committee on Defense Production 1978:1:3-4]:

At the close of World War II, the terms "preparedness" or "readiness" had an almost exclusively military connotation. To the extent that they applied to civilian activities, these terms related to prudent measures deemed necessary to protect the civilian populace against enemy attack or to assist in converting the civilian economy to a wartime footing.***

In the intervening decades, however, the term "preparedness" has come to have a much broader significance. It now includes not only measures aimed at securing the country's defenses and the protection of the population, but also a host of activities designed to prevent or mitigate the effects on persons and property of natural disasters, resource crises and other economic disruptions, industrial and transportation accidents--such as nuclear powerplant emergencies, spillage of flammable or corrosive chemicals, train derailments--and certain forms of terrorist activity.

The growth in the significance of the word preparedness, although little remarked, has resulted primarily from...(1) the increasing vulnerability of a complex, highly interdependent industrial society, and (2) the increasing demands made on Government by citizens whose lives may be dramatically affected by...emergencies they are unable to prevent or control.

***[The "Murphy" Commission on the Organization of Government for the Conduct of Foreign Policy, June 1975, found]...an overemphasis on

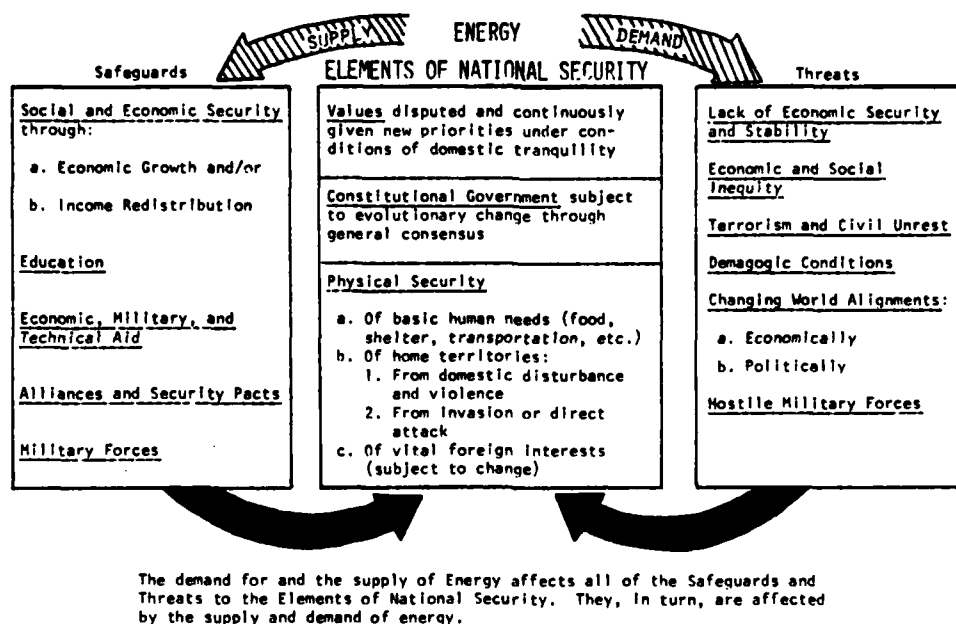
...security defined in narrow military terms as against broader security considerations and broader "economic", "foreign policy", and "domestic" concerns. In fact, given most people's views about today's problems and the problems of the next decade, the structure of the 1940's is no longer appropriate. Even for security against physical threats to American life or property, armies no longer fully suffice. [Emphasis in original.]

Citizen concern for protection against a tornado, a nuclear power-plant meltdown, a flood, or a prolonged cessation of vital transportation reflects the commonsense understanding that the security of life and property is composed of more than defense against enemy invasion or coercion. This is not to underrate the significance of armies. It is rather to give full meaning to the idea of securing the general good of the populace.

Again, attacking historical but artificial distinctions [id.:34-35]:

Among the most serious of recent trends is the tendency to make nuclear attack preparedness an entirely separate and distinct function from peacetime emergency preparedness. This is of particular concern in view of the mounting evidence of increased social and economic vulnerability to non-military threats or disasters. A rigid distinction of this kind also contradicts the experience of most planners that the most important preparedness functions are non-specific as to type of disaster and that programs directed against the most common types of peacetime disasters provide an excellent base for nuclear attack response.

This enlarged conception and operational structure of preparedness reflects a broad evolutionary view of its changing mission [Hermann 1977]. As Bucknell [1979:4-11] summarizes the task:



An awareness of the broader energy vulnerabilities of our society, then, suggests such national security objectives as:

- Essential self-reliance and sustainability in vital resources, including energy. Since many of these resources are procured from developing countries, this implies attention to their continued willingness to sell those resources, hence to their economic and political stability and well-being.
- Resource-distribution and -use systems capable of tolerating sudden, major decreases in supply of key resources, singly or in combination.
- A flourishing, adaptive economy, free of "choke points" in which disruptions could have critical national impact [Joint Committee on Defense Production 1977:II:34].
- Domestic and international financial institutions designed to ensure integrity, promote stability, and deserve confidence.
- Avoidance of large-scale public and occupational health and safety hazards arising from the energy system.
- Protection of ecological variety and stability, with special attention to natural materials cycles, climate, and the basis of long-term biological productivity (e.g. in agriculture).
- Domestic tranquility, based on social justice, pluralism, and shared respect for democratic values.

The price of failing to achieve these objectives can readily be framed in economic terms, for example in the Undersecretary of State's concise account of interconnections within the non-military world oil problem [Cooper 1978:244]:

If our nations do not prepare for the oil shortfall in the 1980's, the framework of international cooperation which we have worked so hard to build since World War II will be imperiled. Severe economic disturbances would be followed in some countries by political instability. The trend toward freer international trade, which has been responsible for much of our post World War II prosperity, would surely be reversed under...recession and oil-induced balance-of-payments difficulties. The prosperity and cohesion of the Western industrialized nations would be at stake, putting in jeopardy our own security and ultimately our way of life.

The non-oil producing developing countries would also be hard hit economically. These nations are not profligate energy users; [they] use very little energy, but their economic development--both in industry and agriculture--depends on the availability of imported energy. If oil prices are rising, the burden on the already fragile external financial condition of these countries would become insupportable. The cost of their imports would rise, and in world recession their exports will contract. Economic development would stop, if not regress.

These conditions would breed international turmoil and foster revolutionary doctrines and political extremism. Speaking of the political fallout from inflation that occurred decades before oil prices started to drive it, Helmut Schmidt, while serving as F.R. Germany's Finance Minister, remarked: "I have only to go to the years 1931 to 1933 to say that the meaning of stability is not limited to prices." [Brown 1977a:33]

Today in America, the inflation, unemployment, and frustration arising from further energy scarcity could endanger "an environment where competing values, needs and interests are resolved lawfully and not through resorts to violence" [Hoover 1979:1]. Simply having to wait in line to buy gasoline has led some Americans to shoot each other. With many other Americans already having to choose daily between heating and eating, and with safety margins of personal survival rapidly shrinking, both hardship and anger would be bound to rise in more dramatic shortages. With them would rise interregional tensions and the problems of declining industrial regions--[p]opulation out-migration, urban decay, declining local tax bases, and increasing social service costs.... Sharing social costs of energy-related unemployment, under-employment,...and so on...exacerbates longstanding and resistant differentials between racial and ethnic minorities...and the majority population." [id.:16-17] "The need for taking rapid and decisive action to reduce energy vulnerability, internal and external, directly clashes with the need for extended debate and compromise to resolve distribution of energy-related benefits, costs, hazards and deficits." [id.:20] Such stresses could lead to civil disorders or perhaps even to domestic terrorism. In this way too, the energy problem hazards our democratic practices, our most deeply held values, and our supreme national interests.

These sources of domestic instability in turn pose military dangers, for

"Deterrence is not...simply a matter of operational hardware. Potential antagonists must also believe that the social and political fabric of the U.S. is sufficiently whole that this force would be employed if the country were threatened by direct nuclear attack. Equally important is [the] perception that the U.S. is sufficiently stable that strategic nuclear forces will not be deployed in a first strike. It is certainly conceivable that the political and social stability of American society could be threatened by economic and social strains of energy scarcity to the point where the credibility of nuclear deterrence is lessened. However, most observers do not see increased vulnerability to direct military attack as the most likely or urgent impact of energy scarcity on U.S. security. Secondary impacts of U.S. failure to deal with energy scarcity are more important. Oil imports of a scale that would put other industrial economies at great risk [are]...an example. [Hoover 1979:2-3]

The military and non-military threats which the energy problem poses to our society are thus intricately interlinked and feed on each other. As Lester Brown's survey of emerging national security issues concludes [1977a:37-40]:

The military threat to national security is only one of many that governments must now address. The numerous new threats derive directly or indirectly from the rapidly changing relationship between humanity and the earth's natural systems and resources. The unfolding stresses in this relationship initially manifest themselves as ecological stresses and resource scarcities. Later they translate into economic stresses--inflation, unemployment, capital scarcity, and monetary instability. Ultimately, these economic stresses convert into social unrest and political instability.***Non-military threats to a nation's security are much less clearly defined than military ones. They are often the result of cumulative processes that ultimately lead to the collapse of biological systems or to the depletion of a country's oil reserves. These processes in themselves are seldom given much thought until they pass a critical threshold and disaster strikes.***The purpose of national security deliberations should not be to maximize military strength but to maximize national security.***The continuing focus...on military threats to security may not only exclude attention to the newer threats, but may also make [their]...effective address...more difficult [by diverting resources from them].*** At some point governments will be forced either to realign priorities in a manner responsive to the new threats or to watch their national security deteriorate.

This study deals with a specific class of threats to national security: those expressed through the energy system, and especially the kind of vulnerability described [Glassey & Craig 1978:330] as "the degree to which an energy supply and distribution system is unable to meet end-use demand as a result of an unanticipated event which disables components of the system. The kinds of events referred to are sudden shocks, rare, and of large magnitude." Later Chapters will develop this theme in detail. This section will first seek to put specific threats ("what can go wrong") and corresponding preparedness measures into context by briefly surveying all types of threats to the security of the United States. Chapters 2 and 3 will consider what these threats can do to energy systems and to specific energy technologies respectively.

1.2. Foreseeable threats.

Identifiable and foreseeable threats to national security can range from natural disasters to aggressive physical acts (war, terrorism, sabotage) to accidental or deliberate failures of complex technical and economic systems. Some have mainly a tangible or economic effect, others mainly psychological (as would be a threat to introduce a potent carcinogen into unspecified water supplies). Collectively, they offer a formidable array of hazards to life, liberty, the pursuit of happiness, and the preservation of democratic values.

1.2.1. Natural disasters.

Perhaps the most familiar threats with which preparedness deals are those commonly called "natural disasters"--though they may in fact be caused or aggravated by human activity. (For example, flooding can be caused by dam failure or by building on a flood plain; unstable climatic conditions may be related to such stresses as carbon-dioxide and particulate emissions, deforestation, and creation of urban "heat islands.") For some "natural disasters" that are sudden and catastrophic, like earthquakes, volcanic eruptions, and tsunamis (tidal waves), the areas at risk are broadly known but the times are not. General precautions, though often inadequate [Los Angeles Times 1981], are commonly taken, such as reinforcement of buildings and upgrading of communications equipment for disaster-relief services. It may soon become possible--some authorities believe it is now possible--to give "suspicion" warnings of such disasters a few days in advance, though this capability raises thorny legal and political questions. Even if foreseen, these disasters might send shock waves through the economy: there is currently Federal concern, for example, that parts of the insurance industry may not survive the \$80+-billion damage of an expected Richter 8+ earthquake in Los Angeles or San Francisco [Smith 1980].

Severe weather occurs frequently in a country as large as the United States. In 1973-75, an average of about three dozen major episodes per year caused damage totalling about a half-billion dollars per year [Joint Committee on Defense Production 1977:I:17-20]. Each region has a characteristic spectrum of such disasters: "hurricanes are especially likely...in Florida, droughts in Texas, tornadoes in Oklahoma, and blizzards in Wisconsin." [id.:17] Other manifestations include windstorms, ice-storms, hailstorms, landslides, lightning, dust-storms, and floods. In 1960 storms which killed 354 people, ice deposits over 8" (20 cm) in diameter built up on wires [Stephens 1970:13]. Tornado winds can exceed 500 mph [id.:23]. Conditions as extreme as any in the world can occur in outwardly innocuous places: in New Hampshire's White Mountains, the officially recorded maximum windspeed is 231 miles per hour, and a tempera-

ture drop of sixty Fahrenheit degrees in forty minutes has been unofficially observed in July. Few parts of the United States are essentially free of risk from extremes of weather, though the frequency of extremes varies widely.

In many areas, "normal" bad weather is also disruptive, with routine snowfalls, spring thaws, ice breakups, etc. snarling transportation and communication for days or weeks each year. This is also common in other countries: in the Soviet Union, for example, "seven out of ten...roads become impassable" during the autumn rains that left the German offensives of 1941 and 1942 bogged down in mud [id:II:22] and during the spring thaw. This can become crucial in coping with non-weather emergencies. For example, civil defense planners have observed that severe winters and frozen ground make winter evacuation of Soviet cities "not feasible"; early summer evacuation would have to rely on depleted food stocks and would interfere with planting "so vital to the weak Soviet agricultural system"; and late summer evacuation would forego harvesting late-ripening crops (i.e. most except winter wheat) [id.]. At least some parts of the U.S. presumably have different but analogous evacuation constraints.

Weather fluctuations can affect wide areas for periods of weeks, months, or (as in the Sahelian drought) years. In the U.S. in 1980-81, extreme cold in the Midwest and Northeast, and extreme heat in the South, caused as much dislocation as a major hurricane, but spread over a far longer period. There is a consensus in the climatological community that global weather patterns in the past decade or so have exhibited considerably greater fluctuations from the mean than earlier in this century and will probably continue to do so [Kirtland 1981]. Though fluctuations are commonly described on a seasonal basis ("this winter is much milder than last"), other time-scales are also important. The Colorado River Compact of 1927, for example, allocated water based on average flows for the previous decade, but subsequent average flows have been smaller by as much as a million acre-feet per year. The abnormality of the Compact's base years has been a fruitful source of litigation ever since [Glassey & Craig 1978:335-6].

Likewise, most of today's hybridized crops have been specially bred for best performance in climatic conditions which, though they seemed normal to plant breeders at the time, were in fact the mildest since the last Ice Age. Persistently more erratic and severe conditions, such as now seem to be emerging, could severely test the ability of plant breeders to readapt--especially since the genetic base is being deliberately narrowed, and many adaptable, primitive strains have already been lost [Myers 1981]. This linkage between agriculture (or, more generally, stable biological productivity) and climate is especially important because of the likelihood that global climate is "almost-intransitive" [Lorenz 1976; Study of Man's Impact on Climate 1971]--that is,

subject to abrupt changes from one mode of behavior to another, brought about by very small, seemingly random causes but, once changed, relatively resistant to changing back again. This feature of many complex feedback systems is explored further in Chapter 4.

It is highly likely that we do not yet know all the potentially important triggers, consequences, and interactions of environmental changes. Consider, for example, one narrow area of concern--the stability of regional and global climate. These are some of the unexpected energy/climate interactions whose existence was first widely revealed during the 1970s:

- "Forcing" the nitrogen cycle by using synthetic nitrogen fertilizer increases the incidental production of nitrous oxide by denitrifying bacteria in the soil (especially if soil pH is reduced by acid rain). Some of the nitrous oxide diffuses up to the stratosphere, where its photochemical products attack the ozone layer, especially above 30 km, thus altering stratospheric circulation patterns. Some analysts believe that near-term rates of artificial nitrogen fixation might be climatically significant [Isaksen 1980].

- Krypton-85 routinely released by nuclear reactors and reprocessing plants can apparently alter atmospheric ionization and hence the distribution of electric charge in the atmosphere (the fairweather potential gradient), with unknown but potentially large effects on nimbus rainfall and other processes important to global agriculture and heat transport. This may become important at concentrations orders of magnitude below those of radiological health concern, possibly including present or near-term levels [Boeck *et al.* 1975].

- An oil spill in the Beaufort Sea, where drilling is now underway, could arguably spread under the fragile Arctic sea-ice, work its way to the surface with seasonal melting on top and freezing on the bottom, make the top of the ice gray in about ten years, increase its solar absorptivity, and so lead to a probably irreversible melting of the sea-ice, with dramatic effects on hemispheric weather patterns [Campbell & Martin 1973]*.

- Fluctuations in the behavior of charged particles in the upper atmosphere over Antarctica have been correlated with power surges in the North American electrical grid--apparently coupled, and amplified by orders of magnitude, through some sort of resonance effect. The climatic relevance of this linkage, if any, is unknown [Park & Helliwell 1978].

These examples could as well have been taken from many other areas of earth science (or from biology or even political and social science) as from climatology. In sum, they represent a cornucopia of disagreeable surprises.

When environmental conditions change, whether they be climatic, chemical, or whatever, different organisms adapt at different rates and to different degrees. This can have consequences at least as serious as the change itself.

*Present soot levels in Arctic air may also be of concern [Kerr 1981].

Under the extreme stresses of a post-nuclear-war environment, for example, many insects are likelier to survive than higher organisms that eat them, because insects can tolerate several orders of magnitude more radiation [National Academy of Sciences 1975]. Plagues of crop pests are a plausible result. Already, considerable outbreaks have been induced by similar differential selection under the much milder stress of biocide application. Seemingly trivial, highly localized environmental change can also cause awkward biological adaptations. For example, the young of the Asiatic clam Corbicula fluminea [Mieher 1980], too small to be stopped by screens, enthusiastically and prolifically adapt to the warmth, protection, and food-laden water flow in the artificial environment of freshwater-cooled steam condensers. Some power plants, pumping little but clams, have had to shut down twice daily to shovel them out.

1.2.2. Deliberate actions.

A second category of threats is those caused by human action, arising either outside the United States (wars, embargoes, interruptions of commerce) or domestically (sabotage, terrorism, etc.). If natural disasters happen to strike a point of weakness, that is an unfortunate coincidence; but malicious actions deliberately seek out and exploit vulnerabilities so as to maximize damage and constrain possible responses. Thus identifiable vulnerabilities can invite matching attacks. Identifiable threats meant to exploit those vulnerabilities elicit responses to reduce them. These responses in turn are bound to have characteristic and perhaps different vulnerabilities--which may be lesser or greater than the original ones--inviting new forms of attack, and so on. This iterative, coevolutionary process reduces total vulnerability only if it carefully anticipates the new vulnerabilities created by responses to earlier ones. Otherwise, a France, seeking to reduce Mideast oil dependence, may become equally dependent on a nuclear-electric grid which (as subsequent sections will suggest) can be turned off even more easily than the oil.

Vulnerabilities can be unexpected by both attacker and victim. The Iranian revolution's dramatic effect on world oil prices was probably as big a surprise to Iran as to oil importers. Vulnerabilities can be exploited accidentally: Iran's bombing of Iraqi oil facilities was meant to hurt Iraq, not Italy, France, Brazil, and India. Surface vulnerabilities may be less important than deeper ones: a military attack meant to maximize immediate damage may do less long-term harm than one meant to hamper recovery [Joint Committee on Defense Production 1977:II:37-38]. Modern, high-lethality nuclear warheads, for example, can encourage recovery-hampering attacks on such points of vulnerability as oil refineries in the United States [id.; infra] and certain Soviet in-

stallations crucial to agriculture. The latter include hydraulic facilities (dams, locks, pumping stations, canals) needed to irrigate or drain four million square miles of otherwise barren farmland, and factories making bulldozers and tractors (over 80% of the latter are made in nine factories) [*id.*:II:65-68]. Both countries appear to have highly vulnerable transportation sectors, but in different ways: the Soviets lack a highly articulated network of rail, canal, and especially road routes, and each is already too overtaxed to take up much slack from the rest, whereas the U.S. has such a network (especially of roads) and of vehicles to run on them, but lacks a secure supply of fuel for those vehicles. (The Soviets shared that problem even in 1948-49, when a U.S. targeting plan for 150 nuclear weapons gave top priority to refineries, especially those producing aviation fuel [Joint Chiefs of Staff 1949/78].) Subsequent chapters will deal more fully with the vulnerabilities of energy systems to various disruptions, including enemy attack: not in any effort to duplicate the extensive analysis that has doubtless been devoted to targeting of energy facilities, but rather because vulnerabilities revealed in war often reflect others that may prove costly in domestic disruptions or natural disasters.

Domestic sources of disturbance, besides sabotage, terrorism, and riots, may include strikes, lockouts, oligopolistic withholdings of supply, and judicial or regulatory restrictions (such as injunctions, permit suspensions or revocations, and declarations of pollution control emergency). Obviously, some of these may carry no intent to cause disruption, and may indeed be pursued with commendable ulterior motives.

1.2.3. Mistakes.

Many modern technical systems are liable to sudden, large-scale failure because they rely on elaborate design and construction techniques whose complexity and technical adventurousness are conducive to serious mistakes. These technical failures are sometimes called "industrial accidents," but "accidents" are always caused by something--ignorance, carelessness, overconfidence, or a combination. Common sites of major failures include buildings, bridges, water or sewage plants, dams, locks, tunnels, aircraft, trains, or containments for toxic or hazardous substances. These failures may be manifested or accompanied by fires, explosions, physical collapses, leaks, spills, etc., often in sequences (derailments causing spills causing fires causing further releases) which greatly amplify the effects (as in the 2-4 kT 1946 Texas City fertilizer explosion [Stephens 1970:74]). Many technical failures could be prevented or mitigated by the design precautions developed for energy systems in later chapters. Though technical failures are not the main focus of this study, they offer cau-

tionary tales. A NASA missile worth hundreds of millions of dollars had to be blown up shortly after launch because a single sign error in a computer program put it on the wrong trajectory. (Analogously, had there been a nuclear war during a substantial period in the 1960s, all U.S. ICBM warheads would reportedly have missed their targets by a large and systematic margin owing to an error in reentry calculations.) A radar image of the rising moon once caused a U.S. nuclear attack alert; when this was fixed, a flock of geese caused a new alert [Dumas 1976,1980]. There were 151 false attack alerts, four serious, in 15 months [Coates 1980]. The great care applied to such matters is clearly not always enough: a fire incinerated three Apollo astronauts on 27 January 1967, and a Space Shuttle nitrogen purge error suffocated a worker on 19 March 1981, in extremely high-technology launch-pad operations where the utmost precautions were presumably being taken. Some technical systems are simply so complex as to exceed the limits of attainable reliability and foresight (pp. 17ff infra).

1.2.4. Command, control, and communications disruptions.

Any system is by definition most vulnerable to disruption through its control mechanisms--those meant to affect its operation most by applying the least perturbation. The management structures and procedures for using these control systems, and the communications systems used to provide their input and convey their output, share in this enhanced vulnerability. As systems grow more complex, the volume and speed of information flow needed to control them grow to the point where only computers can cope with it. Computers' indiscriminating willingness to do what they are told, however nonsensical, increases control vulnerability by further concentrating in one place (albeit perhaps accessible electronically from many other places) the ability to affect much by little. For example, a Swedish Government assessment of "The Vulnerable Society" [Wentzel 1979:4] notes that the central computer of the National Social Insurance Board, in the northern town of Sundsvall, sends over 50 million payments or financial messages per year (at a peak rate of half a million per day) to Sweden's eight million people. Computer failure "would affect large numbers of [people]..., chiefly those...with the least social and economic protection. [Non-military] threats to the computer...might include terrorism for political purposes, fire or water damage [or disruption by magnetic or electric fields or by reprogramming]. Even a lengthy power cut might have serious repercussions. Other critical situations might arise, for instance, from an industrial dispute involving personnel working with the computer." [id.] Small groups of systems analysts and programmers, even disgruntled individuals, can now constitute a national threat--which is why Swedish computer experts are being compartmentalized to "redistribute dependence among [more] people" [id.:7].

The Sundsvall computer's product is information, including instructions to transact financial affairs. The product of energy systems, however, is delivered electricity, oil, gas, etc. Their designers have tended to concentrate on ensuring the supply of that product, rather than on ensuring proper control of the information internally controlling that delivery. Most assessments of energy vulnerability, likewise, deal with crude disruptions--oil embargoes, pipeline or transmission-line sabotage, etc.--when in fact the greatest vulnerabilities may well lie in misuse of control systems. This subject is explored further, with specific examples, in the next two chapters.

The first practical demonstration that the worst vulnerabilities may arise within control systems is today coming not from energy systems but from telephones. Highly intelligent and dedicated "phone phreaks" (or, as they prefer to be called, "communications hobbyists") are causing serious loss of revenues for both public and private telecommunications companies in the U.S. An estimated 20% of the traffic on ARPANET is unauthorized. Some supposedly secure military communications links have been accidentally penetrated by experimenting students. The phone phreaks' ingenuity keeps them generally several steps ahead of security precautions. Using microcomputers, they can break codes and find passwords by automatic dialling. They collaborate pseudonymously via computer teleconferencing networks and newsletters, some of which are specifically devoted to technical measures for fooling control systems into giving something for nothing (such as free phone calls, tele~~x~~, water, electricity, gas, photocopying, computer time, and cable TV). Some newsletters of "anti-system technology" focus even more narrowly on ways to "crash" telephone and time-sharing computer systems--an occasional result of random intervention, but much easier to accomplish with understanding and purpose. It appears that one person, without compromising identity or location, can crash most or all of a corporate or commercial telephone network and keep it down more or less indefinitely, perhaps causing significant damage to electromechanical components in the process. Most, and with sufficient effort perhaps all, communications systems whose entry is controlled by electronic passwords rather than by physical barriers are vulnerable to penetration, misuse, and perhaps disruption.

Physical barriers, of course, are not an absolute bar to physical penetration by stealth or force. The physical vulnerability of some control systems, like the control room of a nuclear reactor, may suggest a need for a remotely sited duplicate control room to be used if the first one is taken over (a proposal already rejected by the NRC, though some alternative control equipment for basic shutdown functions is provided). But such duplication also increases vulnerability to capture, or simply to interception and misuse of the communications channels, as in computer and telephone networks today. False control

signals can then be combated by encoding, but this increases operational delays and errors: recall the 37 minutes it took for a technician to find the "all clear" tape after accidentally broadcasting a tape announcing a Soviet nuclear attack [Dumas 1980:18f]. In this game of threat and countermeasure, problems simply cascade: the design principle seems to be "One damned thing leads to another" (a theorem familiar to nuclear designers who find many accidents arising from safety systems' failing or interfering with each other). To the extent that deliberate intervention in a control system can be combated, it is seldom by adding yet more layers of complexity, but by a quite different strategy of resilient design (Chapter 4).

The vulnerability of controls is especially marked in computerized financial systems. An adversary could probably crash the U.S. (and international) banking system simply by using electronic funds transfer (EFT) to make many billions of dollars vanish instantaneously. In 1980, four 13-year-olds brought chaos to some Ottawa commercial computers while playing with a microcomputer at their New York private school [Friedman 1980]. Fraud, sabotage, and coercion using EFT has already reached alarming (if largely unpublicized) proportions. If a computerized embezzlement is detected (many cannot be), that fact itself is frequently an effective lever for blackmail, lest the victimized organization lose public confidence or have to pay higher insurance premia. It is doubtless encouraging to potential computerized thieves that of the few caught so far, most have been rewarded with lucrative jobs as security consultants.

1.3. The chain can be more vulnerable than its weakest link.

The foregoing survey of threats to national security--brief and far from comprehensive--is altogether too sanguine, for it has not yet related potential disruptions to the complex interdependencies of the systems in which they act.

As a pioneering study of vulnerability [Dresch & Ellis 1966:3] declared:

This study is concerned with total vulnerability, or more precisely with the vulnerability of the totality--the whole nation as a social system. It is thus concerned with developing a methodology for assessing the chances of this system surviving without drastic or significant change in its essential characteristics, without fatal impairment of its capacity for regenerating damaged parts or subsystems, and without sustaining stresses, tensions, or flaws fatal to its normal evolution and its normal processes for adjusting to environmental change.***

It is conceivable that components or subsystems could be identified that are vulnerable to attack and that their loss would destroy the nation in some important sense. It also is conceivable that other components might be highly vulnerable, but that the system has the clear capacity to restore those components or to get along without them. The assessment of vulnerability, therefore, cannot rest on a mechanical collection of assessments of the vulnerability of separate parts. [Emphasis added.]

"Mechanical collection," however, is what most vulnerability studies do. At best, they assess energy vulnerability (for example) by concatenating the individual vulnerabilities of fuel sources, processing plants, storage and transmission and distribution facilities, etc. But this reductionism ignores the crux of the problem: interactions, combinations, feedback loops, higher-order consequences, and links across the system boundary. The complexity of these links may defy analysis, though not anecdotal illustration.

1.3.1. Common-mode failures.

Any system, for example, is subject to "common-mode" failure (p. 146n), as when several supposedly independent valves all fail for the same reason--perhaps because of a common design flaw or because they are all exposed to conditions in which they cannot survive or because they all suffer a power failure. Common-mode failures cannot be identified simply by cataloguing individual failure modes or probabilities. In a spectacular example, the afterheat removal system in the Oak Ridge Research Reactor failed for several hours during operation on 19 November 1969 even though it had three identical channels backing each other up [Epler 1970]. In each channel, there were three separate operator errors, two equipment installation errors, and three design errors (one of which did not affect the outcome because the circuit in which it occurred was inoperable for other reasons). The system would have worked if any one of these 21 failures (seven identical errors or equipment failures in each of three channels) had not occurred. "This is almost unbelievable, especially in view of the importance that is attached to the single-failure criterion wherein no single failure shall prevent proper [operation]....***It must be concluded that present tools and methods are ineffective in uncovering the source of common mode failure....[R]eliability analysis would have uncovered nothing. The single-failure analysis would also have been ineffective." [id.] Damage to the core was prevented only because a less reliable backup system, which the failed ones had replaced, happened still to be available and functioning.

The causes of other common-mode nuclear safety failures are legion. In one memorable case, a technician adjusting the trip points in several supposedly independent safety channels happened to calibrate them all to an inoperable range simply by setting his voltmeter selector switch on the wrong decade position. In another case, a key circuit failed because a test procedure simultaneously destroyed a diode and confirmed that it was in good order. A popular sampler anthologized from official reports of such incidents [Pollard 1979] notes common-mode failures from such diverse sources as power-supply outage [id.:17], disabling of four power sources when a failed transformer hurled

a lead across a 69-kV bus [:28], incorrect installation [:30] or manufacture [:70,70,73], cold solder joints [:48,65], floats that leaked, filled up, and sank [:50], wiring errors copied onto wiring diagrams [:51], water damage from outside component storage [:57], contaminated lubricating oil [:61], clogged pump inlet strainers [:62], pipes frozen by the failure of a miswired heater thermostat [:63], and unknown causes [:11]. In one instance, control rods moved out when commanded to move either in or out [:17] because the two-phase, three-wire drive motor, after one wire became disconnected, could start up on the remaining phase--supposedly an impossibility--owing to an interaction with the windings of a cooling-blower motor wired in parallel with the drive motor. In another case [:22], relays designed to be fail-safe, opening if their power failed, stuck shut because of sticky paint: similar relays had proven highly reliable for 30 years, but new staff at the manufacturer's new plant had put the paint on thicker.

1.3.2. Unpredictable interactions.

The sheer complexity of many technical systems can defeat efforts to predict their failure modes. "The sequence of human and mechanical events leading to the two most serious power reactor failures in the U.S. [at Browns Ferry and Three Mile Island] were excluded from fault tree analysis in the most comprehensive study of reactor safety ever undertaken [Rasmussen *et al.*, NRC 1975]. Clearly it is possible to construct systems sufficiently complex that all probable states of the system are not foreseeable." [Hoover 1979:53] A 29-cent switch burned out by improper testing caused grotesque failures to cascade throughout the Apollo 13 spacecraft [Cooper 1973]. In 1980, as simple an initiating event as dropping a wrench socket down an Arkansas missile silo led to the explosive ejection of a megaton-range Titan warhead into a nearby field.

The complexity of even the most advanced technical systems, however, is dwarfed by that of biological and social systems, as a simple example illustrates [Holling & Goldberg 1971:222]. The World Health Organization attacked malaria-carrying mosquitos among the inland Dayak people of Borneo with verve and abundant DDT. The people became much healthier, but their roofs started falling down. The DDT had killed a parasitic wasp which had previously controlled thatch-eating caterpillars. Worse, the cats then started to die: they had built up lethal doses of DDT by eating geckos which had eaten poisoned caterpillars. Without the cats, rats flourished. Faced with sylvatic plague, the WHO had to parachute cats into Borneo. "We cite this example," the authors remark, "not because it has great substance, but...because it shows the variety of interactive pathways that link parts of an ecological system, pathways...

[so] intricate...that manipulating one fragment causes a reverberation throughout...." [id.]

A further example [id.:223] extends the concept. Farmers in the Cañete Valley on the coast of Peru shifted in the 1920s from sugar cane to cotton. This developed an economically tolerable infestation by seven native insect pests. In 1949, persistent, highly toxic, broad-spectrum pesticides, such as DDT and toxaphene, because cheaply available for distribution by aircraft throughout the confined valley, offering an opportunity to decrease crop damage dramatically and hence increase yields and profits. That initial result was followed within a few years, however, by the emergence of six new cotton pests that had not previously been a problem; then, six years later, by the return of the original seven pests, now equipped with pesticide resistance. Despite heavier and more frequent spraying and the use of organophosphorus insecticides, "the cotton yield plummeted to well below yields experienced before the synthetic pesticide period. The average yield in 1956 was the lowest in more than a decade, and the costs of control were the highest." The near-bankrupt farmers were forced into a sophisticated program of integrated pest management based on reformed farming practices, minimal use of biocides, and fostering of beneficial insects. As any ecologist might predict, once biological balance was restored, pest levels dwindled and yields increased to the highest levels in the valley's history. This is, however, a story of luck. The farmers might well have caused irreversible damage: their effort to achieve a narrowly defined objective (eliminating seven insect pests) in the cheapest and simplest way had generated "a series of unexpected and disastrous consequences explicitly because of the narrow definition of the objective and the intervention."

The Borneo and Cañete examples, Holling and Goldberg note [id.:224], "illustrate four essential properties of ecological [or other complex] systems":

By encompassing many components with complex feedback interactions between them, they exhibit a systems property. By responding not just to present events but to past ones as well, they show an historical quality. By responding to events at more than one point in space, they show a spatial interlocking property, and through the appearance of lags, thresholds, and limits they present distinctive non-linear structural properties....[E]cosystems are characterized not only by their parts but also by the interaction among these parts. It is because of the complexity of the interactions that it is so dangerous to take a fragmented view, to look at an isolated piece of the system. By concentrating on one fragment and trying to optimize the performance of that fragment, we find that the rest of the system responds in unexpected ways.

By applying these biological insights (Chapter 4) to urban renewal, rent control, and freeway construction, Holling and Goldberg [id.:227-228] were even able to predict and explain results that had long baffled analysts of urban socioeconomics.

These properties of natural and social systems--properties derived from their very complexity--are precisely those that are critical, as Brown [1977a] argued above, to the conceptual basis of effective preparedness. Viewing security as solely an outgrowth of military strength (whose impact is as narrow and double-edged as that of the Cañete Valley pesticides) dangerously neglects the effect of economic, ecological, and social disturbances on the very systems one is seeking to secure. Focusing on one aspect of security at a time ignores the interactions among all aspects. Subtle, higher-order interactions can be a greater threat than direct, first-order consequences.

Where cause-effect relationships are too complex to understand intuitively, attempted solutions can make the national security problem, or other problems, worse: the cause of problems is often prior solutions. Some systems analysts, such as the mathematician Roberto Vacca [1974], believe that poorly understood interactions may prove collectively so unmanageable as to lead to the breakdown of industrial society. The Swedish vulnerability study [Wentzel 1979:2], citing this view, found "similar apprehensions among technicians, biologists and sociologists." Perhaps an extended qualitative illustration [Lovins 1977b:10-11] can convey the flavor of these unexpected interactions, feedback loops, and potential instabilities in modern techno-economic systems and how they bear on energy preparedness. The following example is of course highly selective, but is not a wholly tongue-in-cheek description of recent trends.

1.3.3. Tracing higher-order consequences.

The United States pursued for many years a policy of promoting the use of more energy while holding its price down through regulation and subsidy. Because the energy looked cheap, its users did not know how much was enough, and grossly underinvested in energy productivity. The resulting emergence of the United States as a massive net importer in the world oil market harmed many U.S. allies. It harmed the economies of some oil-exporting countries which were being asked to lift oil at a rate detrimental to their reservoirs or economies or both. It devastated the Third World, which was unable to compete for the oil. The value of the dollar fell. Dollar-denominated oil prices rose. The U.S. then needed even more foreign exchange to pay for the oil. It earned this in three main ways: depleting domestic stocks of commodities (which was inflationary, left the forests looking moth-eaten, and left holes in the ground where orebodies used to be); exporting weapons (which was inflationary, destabilizing, and of controversial morality); and exporting wheat and soybeans (which inverted Midwestern real-estate markets and probably raised domestic food prices). Exported American wheat, until embargoed, diverted Soviet

capital from agriculture to military activities, increasing pressure on the U.S. to raise its own [inflationary] defense budget--which it had to do anyhow to defend the sea-lanes to bring in the oil and to defend the Israelis from the arms sold to the oil-exporting Arabs. (From this point of view, the best form of Middle Eastern arms control might be American roof insulation.)

With crop exports crucial to the balance of payments, pressure mounted for even more capital-, energy-, and water-intensive agribusiness. Fencerow-to-fencerow planting and cultivation of steep and marginal land raised soil-loss rates to levels exceeding to those of the Dust Bowl, with a dumptruck-load of topsoil passing New Orleans in the Mississippi River each second--not counting soil that was compacted, burned out, or sterilized. Heavy chemical inputs and a severely narrowed genetic base impaired free natural life-support systems. Still more oil was needed for fertilizers, pesticides, herbicides, irrigation, and desalination. All of these increased the stress on remaining natural systems and threatened uncontrollable epidemics of crop pests with an evolved resistance to chemical pesticides. More energy was needed to pump the vanishing groundwater from greater depths and to purify drinking-water contaminated with nitrate runoff. More coal strip-mines and power plants, using still more water and land, were needed to supply the energy. The capital intensity of modern agribusiness, coupled with fluctuations in markets and weather, became unsustainable in the 1980 recession when land values (on whose inflation farmers had borrowed heavily to pay their carrying charges) stopped inflating, instantly creating thousands of mini-Chryslers out of Midwestern farms.

The spiral sped faster as artificial financial incentives demanded quicker returns. The Ogallala Aquifer under the High Plains was drawn down one to three meters per year and recharged less than a centimeter per year. It was already half gone when the lifting rate, during the four dry months of the year, surpassed the full annual flow of the Colorado River past Lee's Ferry. Two-fifths of America's feedlot cattle came to be grown on grains made of Ogallala groundwater. Growing enough of that grain to put enough weight on a feedlot steer to put an extra one pound of meat on the table came to consume about a hundred pounds of lost, eroded topsoil and over eight thousand pounds of mined, unrecharged groundwater [Jackson 1980; Jackson & Bender 1981]. To replace imported oil, some people started to make the corn into ethanol fuel, but because of the unsustainable farming practices, each bushel of corn consumed about two bushels of topsoil [id.].

Meanwhile, excessive substitution of apparently cheap inanimate labor exacerbated structural unemployment. A tax system left over from an era of plentiful capital and scarce labor, and therefore designed to subsidize capital investment and tax employment, also increased unemployment. This worsened

poverty and inequity, which increased alienation and crime. High oil prices and the collapse of the automobile industry hastened the decay of the urban Northeast. Priorities in crime control and health care were stalled in part by the heavy capital demands of building and subsidizing the energy sector, which itself--by its extraordinary capital-intensity and its noxious emissions--contributed to the unemployment and illness at which those investments were aimed. Energy prices and oil balance-of-payments deficits helped to drive inflation. Inflation and unemployment fed civil unrest. The growing vulnerability of the energy system to strikes, sabotage, and protest required greater guarding, surveillance, and erosion of civil liberties. These encouraged the beginnings of a drift towards a garrison state. This drift, coupled with consolidation of oil and uranium cartels and a widespread failure to address the energy security needs of developing countries hit hardest by oil prices, encouraged international distrust and domestic dissent, feeding further suspicion and repression. On the horizon loomed energy-related climatic shifts that could jeopardize agriculture, especially in the Midwestern breadbasket, so endangering a hungry globe. The competitive export of arms, reactors, and inflation from rich to poor countries made the world more inequitable, tense, and anarchic. Plans proceeded to create, within a few decades, an annual flow of tens of thousands of bombs' worth of plutonium as an item of commerce within the same international community that had never been able to stop the heroin traffic. Nuclear bomb capabilities crept towards the Persian Gulf from several directions.

All this is rather a lot, of course, to blame on underpriced energy. But the point of this informal, slightly whimsical tracing of some possible consequences is that the elements of national security must be considered as an interdependent whole. Their bizarrely intricate connections keep on working whether we perceive them or not.

1.4. Surprises.

We do not yet have, and may not have for a very long time if ever, all the information we need to foresee all important consequences of our actions. This does not mean that we dare not do anything. It does mean that we need to view any reductionist catalogue of national security concerns with a certain wariness and humility, knowing that it cannot capture the range of surprises from without, or the higher-order interactions within, that together almost certainly dominate total risk.

In 1974, one of us (ABL) made a list of the twenty most likely surprises in energy policy over the next decade or two. Near the top of the list were "a major reactor accident" and "a revolution in Iran." Number twenty on the list, of

which no examples could be given, was "surprises we haven't thought of yet." There will be many of those, not only because there is so much still unknown about how the world works, but because rare events do happen. A principle enunciated by George Orwell and E. B. White, and known to discomfited experimental scientists as the Totalitarian Law of Physics, states that "Whatever is not forbidden [by the laws of physics] is compulsory"--it will happen sooner or later. There are many possible events which may be individually very rare: their probability may be vanishingly small. But these surprises are also almost infinitely numerous, so they will catch up with us, and one or another of them is likely to occur fairly frequently. We live in a world full of nasty surprises, and had better prepare for it.

National security, therefore, requires not only that we calculate the probability of foreseeable kinds of failure, but also that our designs include the broader philosophy of resilience in the face of the incalculable: lunatics, guerrillas, Middle East wars, freak winters, social turmoil, unpredicted high-technology failures. True preparedness requires not merely an explicit readiness for foreseeable threats--the subject of the next two chapters--but also an implicit readiness for unforeseeable and imponderable threats. The theme of unforeseeable threats to complex, interactive systems, and the design principles for resilience that flow from the inevitability of such threats, will return for full development starting in Chapter 4.

2. GENERAL VULNERABILITIES OF THE U.S. ENERGY SYSTEM

2.1. What makes the energy system vulnerable?

Most commercial fuels and power in the United States today are delivered by processing and upgrading fossil fuels in relatively remote, centralized plants, then distributing the concentrated, high-quality product via elaborate transmission networks to dispersed users. These processes depend on massive, highly capital-intensive, long-lead-time facilities of high technical and social complexity, operating continuously under precise controls.

The familiarity and usual dependability of this system encourage a belief that it will continue to resist disruption in the future. But the purpose of vulnerability analysis is to ensure preparedness, not necessarily to defend the status quo. In fact, as we shall show, the very properties of the modern energy system that make it such a visible and impressive technical achievement also make it peculiarly vulnerable to the threats described in the previous Chapter. Each property just listed contributes to this latent vulnerability in ways we shall now describe under the following topics: dangerous materials, limited public acceptance, centralization of supplies, large haul lengths, limited substitutability, unique characteristics of grid electricity, inflexibility of delivery systems, high capital intensity, long lead times, specialized labor requirements, control problems, and possible adaptability of fuel delivery systems to delivering other substances instead. Chapter 3 will apply this generic discussion to some specific energy technologies; first, selected examples will illuminate the structural properties of the energy system.

2.1.1. Dangerous materials.

Many of the forms in which energy is commonly delivered are hazardous in their own right. Though accidental electrocution is uncommon, defective electric wiring is among the leading causes of fires (with poorly installed and maintained wood stoves gaining on it fast). But the main danger arises from the deliberately high energy density of fuels--the energy carriers which, by direct combustion, supply 87% of U.S. delivered energy. A gallon of average gasoline, for example, contains as much energy as a strong horse produces in 49 hours' work. A standard gasoline pump (say 50 liters per minute) delivers fuel energy at the remarkable rate of 29 thermal megawatts; thus a 20-pump station, when all its pumps are working, is delivering energy about as fast as a 600-MWe power station [Foley 1979].

Such fuels are, by intent, highly flammable or explosive. The amounts of fuels present even in their most dispersed stages of distribution, such as tank trucks, are sizable hazards. A 9000-gallon tank truck of #2 fuel oil contains the energy equivalent of a small (0.3 kT) nuclear explosion (although if it burned, the energy would appear not as prompt radiation or blast but as radiant heat sufficient to melt nearby cars). In refinery accidents, burning oil flows have covered as much as 17 hectares--an essentially unextinguishable conflagration--and vapor explosions have devastated as much as 12 hectares [Stephens 1970:69,96]. The hazard is not limited to petroleum-derived fuels: at least one worker was killed in the 6 March 1981 explosion of a 680-m³ ethanol tank in São Paulo, Brazil [Los Angeles Times 1981b].

Gaseous fuels, being harder to contain, increase the hazard: "With vast quantities of a highly explosive substance [natural gas] being carried at very high pressures in a steel pipeline with a wall thickness ranging from 1/10" to 1/2", often near or through populated areas, the potential for catastrophe is considerable." [Congressional Research Service 1977:I:13] "A gas pipeline can be bombed over a considerable length by a single charge. It will blow up by itself if a break allows air into the line. An air-gas mixture, under [the] right conditions, can explode and detonate over miles of terrain, through cities and industrial centers....The writer observed an 8-inch spiral weld line that unwound and came out of its ditch for a distance of 8 miles. A larger line would result in a worse situation. Detonation can occur even in a 2-inch line." [Stephens 1973:34-35] Compared to, say, piped water, this is an impressive potential for mischief, demanding meticulous care. Such energy density increases the likelihood of serious consequences from an initial disruption, whether from natural disaster, deliberate attack, or technical failure. The ready availability of such materials as natural gas, propane, and gasoline also expands the destructive capability of terrorists by making it relatively simple for them to improvise fuel-air explosives whose detonation inside major, heavily reinforced structures can demolish them.

Another manifestation of high energy density is the radioactivity of nuclear materials. Pure fissionable materials have over a million times the energy per unit volume of pure hydrocarbon fuels. They are mildly radioactive; many of their fission and activation products, intensely so. Despite extensive precautions, the possibility remains of accidental or deliberate releases; and since the threat is insensible and can have long-term consequences with high emotional impact, even the possibility of a minor release can have major social effects. "More than any other type of peacetime disaster,...nuclear emergencies could cause mass panic....[T]he prime danger comes...from the [wide] dis-

persal of radioactive material..., impossible to detect without special instruments, [and which] could cause fearsome and unpredictable consequences: cancer, sterility, and gross birth defects...for many years after...release." [Joint Committee on Defense Production 1977:I:29] Since many of these effects are indistinguishable (even statistically) from those arising from other causes, the perpetrators of a release can be blamed for far more harm than they did; conversely, people cannot be sure the release was not the cause of their affliction, and actual victims may be unable to prove causality as a basis for just compensation. These perplexing issues, now being raised in class actions by persons exposed to the Three Mile Island releases and to fallout from military nuclear weapons tests in the 1950s, have aroused considerable public attention and anxiety.

2.1.2. Limited public acceptance.

Such anxiety is only one of many sources of broadly based, ideologically diverse reluctance to bear the social costs of major energy facilities. The sources of opposition include a desire to preserve a particular way of life (an important issue in rural Western areas threatened with boom-town development); concern about a wide range of environmental impacts (water use, loss of habitat or endangered species, biomedical effects of electric fields from high-voltage transmission lines, safety of LNG or nuclear plants, oil pollution, nuclear proliferation, noise, coal dust, heat releases, esthetics, etc.); desire to defend certain social structures or values (free enterprise, small business, local self-reliance, etc.); or even perceived vulnerability itself. It does not matter here how far these diverse concerns are justified or how widely they are shared; the important thing is that they represent views sincerely and strongly held by citizens of a democracy who believe they are entitled to give their views political and practical effect. Many historical examples suggest [Lovins 1979,1980a] that efforts to bypass or suppress such concerns bear high political costs and often turn out in hindsight to represent a refusal to listen to advance warnings of serious errors in policy. For present purposes, however, it is sufficient to note that major energy facilities of any kind--like highways, water projects, chemical factories, toxic-waste dumps, etc.--can come to represent to many people a highly visible focus for both project-specific and broader grievances. By threatening direct and undesired impacts, by embodying social diseconomies of scale (Chapter 5), or by symbolizing other perceived inequities, such a facility can be, from the standpoint of civil disturbances, an attractive nuisance*. Nuclear facilities,

*And can have troublesome civil-liberties implications (see references, p. 62).

besides their technical vulnerability (Chapter 3), are clearly among the most prominent lightning-rods for such social tensions [Foley & Lönnroth 1981:25]: hence several studies, e.g. by Bass et al. [1980], on the potential for criminal acts against nuclear power programs motivated partly by opposition to them.

2.1.3. Centralization of supplies.

The geographic separation of primary energy sources (oil and gas fields, coal mines, dams, etc.) or of conversion facilities (refineries, power plants, etc.) from final users has two obvious physical results: it concentrates the facilities themselves into a small area, more vulnerable to all sorts of disruptions, and it makes the connecting links longer and hence more tenuous (as quantified below). But a more subtle social result of this separation may be equally important: the automatic allocation of the delivered energy and of its side-effects or social costs to different groups of people at opposite ends of the transmission lines, pipelines, and rail lines. This divorce of costs and benefits is considered admirable at one end but, often, unjust at the other. To put it baldly, politically weak rural people do not want to live in "zones of national sacrifice" for the benefit of "slurbians" a thousand miles away.

Further, the very scale and complexity of most modern energy projects tends to organize their planners and builders into particular patterns which may be, or at least appear to be, remote and unresponsive to local needs. These trends have together led in the United States to more than sixty "energy wars" --violent or near-violent siting conflicts--now in progress. They reflect an intensity and breadth of social unrest that any student of energy vulnerabilities must take seriously. Archetypical, perhaps, is the long-running rebellion [Casper & Wellstone 1981] by politically conservative farmers in northern Minnesota who nightly dismantle high-voltage power lines that have been built diagonally across their land through a political process that they consider unjust and illegitimate. An anthropologist who has named, analyzed, and often successfully predicted the course of this and other "energy wars" [Gerlach 1979; Gerlach & Radcliffe 1979] persuasively argues that they often reflect an underlying conflict between a network and a hierarchy; the network generally wins.

Additional social feedback loops can further heighten the risk that social unrest will spill over into deliberate disruption of energy systems. For example, the economic insecurity or inequity that massive energy projects may bring to both ends of their distribution systems tends to increase tension and conflict. The perceived risk and social unattractiveness of the projects and the difficulty of siting and guarding large numbers of plants may in turn heighten

pressures for further centralization in remote, paramilitarized enclaves like "nuclear parks" [Burwell et al. 1979; Nuclear Regulatory Commission 1976b], built perhaps on the energy scale of the Mideast oilfields [IIASA 1981]--the same scale whose vulnerability had been the rationale for nuclear power.

2.1.4. Long haul distances.

Most energy sources in the United States have become far more centralized than their customers. The distribution distances required by this disparity can be roughly quantified. For example, a 1-GWe (1000-MWe) power station occupying a site of about 10 sq km, including the area of its coal depot or nuclear exclusion zone, represents a source whose power density (1 kWe/m^2) is four to five orders of magnitude (factors of ten) greater than the average density of electricity consumption [Baughman & Bottaro 1976; p.167]. That average density use corresponds to an average service radius, for a 1-GWe plant, of about 150 km (90 miles). In fact, for a marginal plant of about 1 GWe capacity, the actual average haul length is about 350 km (220 miles) in the United States, or about 100 km (60 miles) in the denser grids of Western Europe. Some electricity travels a far greater distance: British Columbia hydroelectricity goes as far as Southern California and Arizona, and some Churchill Falls (eastern Canadian) hydroelectricity probably gets nearly to Florida.

The average barrel of oil lifted in the U.S. is transported a total of about 965-1290 km (600-800 miles) before final use [Energy & Defense Project 1980:11]. The average unit of natural gas probably moves even further. In 1974, 66% of U.S.-mined coal was hauled an average of 485 km (300 miles) by rail, and 21%--especially in the Ohio River Valley--an average of 775 km (480 miles) by barge [Congressional Research Service 1977:1:62-63,77]. Remote Western strip-mining and exploitation of Arctic and offshore petroleum resources will considerably increase the average haul lengths. "The average distance we have moved our energy sources has continuously increased..., and all signs point to an even greater extension of these vital supply lines." [id. 1:2] Longest of all--halfway around the world--are the supply lines for Mideast oil.

These long haul lengths increase vulnerability to all the types of hazards noted in Chapter 1. Different fuel delivery systems, of course, have different vulnerabilities. "The pipeline network [in California] contains fewer parallel links than the highway net, and has less excess capacity for carrying fuel. Therefore, it is more vulnerable to disruption by earthquake. However, it is less vulnerable to a Teamsters' Union strike." [Glassey & Craig 1978:330-331]

Historically, the greatest concern about fuel and power transportation has been that, being outdoors and over long distances, "A large portion of the fuel

movement...in the United States is vulnerable to disruption from inclement weather, and all forms of fuel shipment are subject to disruption by natural disaster." [Congressional Research Service 1977:III:189] In the cold winter of 1976-77, for example, "The Ohio River froze bank to bank[,] blocking barge traffic in both fuel oil and coal. Coal [wetted at the mine face to suppress dust] froze solidly in rail cars, sometimes requiring blasting to remove it. Winter snows impeded truck movements of heating oils, gasoline, and LPG." [*id.* 189] The seriousness of such effects depends on the mix and flexibility of fuel use in the area. For example, the Ohio River's freeze was especially disruptive because the regional dependence on coal that made the 109-day 1978 miners' strike [Ackermann 1979] so disruptive in the Midwest [Subcommittee on Energy & Power 1978:17] coincided with a regional dependence of coal movements on barges. "Water carriers are, by and large,...most subject to weather...--freezing, flooding, and drought [which reduces allowable draft and constrains navigable channels] can all have very disruptive impacts." [Congressional Research Service 1977:III:191]

Slight differences in the nature of the disruption can greatly change its consequences: the winter of 1977-78, though nearly as cold as 1976-77, caused virtually none of its dislocations in fuel delivery [Kellogg & Schwabe 1981: 63], both because the local details of interference with shipments differed and because people were better prepared the second time. But a great variety of circumstances is available to test the energy system for potential weaknesses. For example [Quirk & Moriarty 1980:90-91]:

- The 1976-77 heating season had 22% more degree-days (a measure of space-heating requirements) and was an average of 1.8°C colder than 1975-76; the 1976-79 heating seasons had 15% more degree-days than 1973-76. (Conversely, the summer of 1980 was about 13% hotter than normal.)

- The 1975-76 and 1976-77 rainy seasons in California were 60% drier than the 1931-77 average.

- There was a global cold spell in 1812-17; in the summer of 1816, frosts were reported every month in New York and New England, and Western Europe had similarly severe weather.

- In the past 70,000 years, there may have been several abrupt drops of temperature by 5°C over large areas; this may occur as often as once every 1,000 to 10,000 years.

Abnormal weather affects both energy supplies and energy demands, giving rise to unpleasant second-order impacts. This is illustrated by the 1975-77

Western U.S. drought [*id.* 91-92], which reduced regional hydroelectric output by about 40%. This deficit made hydro-dependent Pacific Gas & Electric Company burn an extra 50 million barrels of oil and was largely responsible for raising PG&E's operating expenses by 30%. Meanwhile, however, water allotments for agriculture--which normally uses 85% of California's water--were reduced by over 60%, and extra groundwater pumping to try to make good this loss used about 1 billion kW-h of additional electricity. (In normal years, California's largest single use of electricity is pumping by the State Water Project.) The interaction between energy and water problems could have been even worse if proposed coal slurry pipelines had been operating: they would have had such a low water priority that their operation would probably have been severely curtailed, contributing to a kind of common-mode failure of supposedly redundant hydroelectric and coal-electric systems.

As drought persisted in the Western states, the Eastern two-thirds of the country simultaneously suffered record cold. This raised heating costs by an estimated \$4-8 billion and increased oil imports by approximately a further 150 million barrels--a total increase of 200 million barrels worth \$6 billion, not an insignificant contributor to a weak dollar and a tight world oil market. The unprepared natural-gas industry burned 12% of its stored inventory in November (compared to zero the previous winter). Some systems were withdrawing gas when they normally injected it. One major pipeline company sold its reserves prematurely; some gas storage areas were so cold that pumping capacity was insufficient to retrieve stored gas [*id.*:94]. Gas supplies ran short, putting over a million people out of work in twenty states and costing up to \$100 million in unemployment benefits. Over 45% of the gas shortfall was in Ohio, already hard hit by disrupted coal and fuel-oil deliveries.

Perhaps the most disturbing feature of this disruptive weather pattern is that the same one that causes Western drought and Eastern cold also typically causes simultaneous cold weather in Europe and Japan [*id.* 97]. It thus offers a potential for severe pressure on world oil markets if it happens to coincide with a supply shortfall. Recent shortfalls have been only by a few percent; a simultaneous north-temperate-zone cold spell could roughly double this magnitude. The possibility of bad weather not only heightens vulnerability to routine shortages or deliberate disruptions of energy supply; the disruption can be deliberately timed to coincide with bad weather. Thus in Britain, the onset of winter is commonly associated with militancy among fuel and power workers in recollection of the effectiveness of the miners' strike in toppling the Heath Government in 1974. Sabotage of electric grids could likewise be timed to coincide with peak loads or major plant outages or both. Whether in

one country or globally, improved energy efficiency (Chapter 6) would offer an effective hedge against these eventualities by greatly reducing both the amount of energy needed and the sensitivity of that amount to weather.

2.1.5. Limited substitutability.

The infrastructure for using fuels, whether directly or via electricity, has been built on the assumption that several competing fuels will always be readily available in essentially unlimited quantities. Each fuel-using device, on the other hand, is usually built to take a particular fuel assumed to be cheaper than its competitors. The lifetime of these devices typically ranges from one to several decades. Until such recent developments as the commercialization of fluidized-bed boilers [Patterson & Griffin 1978], it was costly and uncommon for boilers to be designed to burn more than one or at most two kinds of fuel--especially to handle both solid and liquid fuels, because they require different kinds of equipment to store and feed them, and the duplication of investment would normally be unattractive. Accordingly, a complex pattern of past investments locks each region and each industry into a relatively inflexible pattern of fuel and power use, limiting its adaptability to interruptions.

This problem is perhaps most familiar to electric utilities, whose plants represent the largest fixed industrial asset in the whole economy. Past fuel interruptions (the 1973-74 oil embargo, the 1978 coal strike, the 1975-77 Western drought, occasional natural gas curtailments, generic nuclear shutdowns) have highlighted regional concentrations on one or another fuel. Utility plans for 1989 [Department of Energy 1981:1:4-12] reflect continuing fuel specialization of different kinds in virtually every region: over 75% coal dependence in the East Central states; over 50% oil in the Florida and Southern California/Nevada regions; over 25% oil in the New York, New England, Northern California/Nevada, and Arizona/New Mexico pools; over 50% gas in South Central; 25-50% nuclear in New England, Pennsylvania/New Jersey/Maryland, Chicago area, and several others; and over 60% hydro in the Pacific Northwest. This might at first sight look like healthy diversity; but it also guarantees that a major interruption in the supply of any of these sources will put at risk the electrical supplies of at least one substantial region.

Substitutability is limited not only between fuels but between different types of the same fuel. There are different kinds of coal whose content of ash, sulfur, and heat vary respectively by one or two orders of magnitude, at least one order of magnitude, and a factor of at least two. Conventional furnaces can burn coal only within a specified, often rather narrow, range of

chemical and physical properties. On a home scale, most stoves perform efficiently, cleanly, and safely with either hardwood or softwood but (in the absence of special design features) not both. Leaving aside the immense variety of refined products (many of which are not interchangeable in end-uses) and considering only crude oil, there are many different kinds differing in specific gravity (heaviness), chemical composition, and trace impurities such as sulfur and heavy metals. Refineries normally need to blend crude oils of different composition--a logistical problem of considerable complexity at the best of times, but one of critical importance. "In some areas of the country large refinery complexes depend on a specific crude oil supply [whose]...interruption ...could shut down [the]...plant. If this refinery were the sole supplier of particular feedstock to a petrochemical plant which was one of a very few making specific products, such as toluene, tetraethyl lead, butadiene, specific solvents, or other chemicals, the loss could be...of strategic importance." [Stephens 1973:14] Refineries designed for low-specific-gravity crudes cannot suddenly switch to high-gravity crudes without developing "bottlenecks" which limit their capacity. Refineries meant for sweet (low-sulfur) crudes are not built of the special alloys required to withstand the severely corrosive sour (high-sulfur) crudes. There are similar restrictions on the purity and heat content of natural gas suitable for various kinds of processing, transmission, and use. Even in storage of liquid fuels, "clean" tanks, barges, tankers, etc. are not interchangeable with "dirty" ones contaminated by crude oil or heavy fuel oils; cleaning vessels is costly and time-consuming. In many complex ways, therefore, prolonged disruption of normal fuel supplies can severely constrain the ability of the fuel-processing and -using industries to improvise. In many cases the modifications needed for (say) oil refineries to switch to a different kind of crude take many months and cost many millions of dollars; it is not just a matter of turning valves [Deese & Nye 1981:40].

2.1.6. Unique properties of grid electricity.

Fossil fuels are in general straightforward and relatively cheap to store in bulk. With reasonable care to protect e.g. piles of coal from spontaneous combustion and tanks of crude oil from gaining moisture, stocks are fairly durable. Nuclear fuels (leaving aside possible safeguards problems) are still cheaper and more durable to store: for a ten-year supply of low-enriched uranium fuel, warehousing charges are infinitesimal and carrying charges add less than 1% to the delivered price of electricity. Electricity itself, however, is uniquely awkward and expensive to store in bulk. This means that the central supply of electricity requires a continuous, direct connection from

source to user. This is not required by any other energy system--not even natural gas, which interposes substantial storage between processing plants and users. It means that interruptions of central-electric supply, having no buffer storage, are instantaneously disruptive. The electrical link is especially fragile because it must not only carry electrons, but carry them in a particular, precisely defined time pattern of variation exactly synchronous with that of the grid. The serious problems of grid stability which this raises are discussed near the end of section 2.2.1.

2.1.7. Inflexibilities of energy delivery systems.

A monumental study of the U.S. energy transportation system [Congressional Research Service 1977:I:84-89] identifies six aspects of system flexibility: adaptability to changes in throughput, fuel used to operate, weather, and routing; ability to build facilities quickly; speed; and ability to handle joint shipments of different fuels. Several of these, plus ability to reverse direction, require brief amplification:

- Volume. Normal fluctuations in demand, let alone the abnormal requirements of substitution for other interrupted supplies, make it desirable to be able to change the amount of energy transmitted, quickly and within wide limits. All present means of coal transportation have this property insofar as they need no fixed or minimum throughput. Railroad and barge traffic cannot greatly expand without overloading key track sectors, locks, etc., but at least within those limits the volume is free to fluctuate. For oil, pipeline routes and capacities are fixed; trucks are highly flexible; and railways and waterways are intermediate in flexibility, having fixed trunk routes but ability to move equipment along them to where it is most needed (and, in the case of railways, to add spur lines). This ability paid off in 1940-42, when the Atlantic Seaboard was 95% dependent (and oil shipments to England were wholly dependent) on coastal shipping vulnerable to German submarines. Twenty thousand idle railway tank cars were reconditioned and put into oil-hauling service "almost overnight" [id.:171-172]. Synthetic rubber tanks and barrel-loaded boxcars were also pressed into service. The oil unit trains "were highballed from one railroad to another" on "fifty railroads and fifty-six routes," achieving a peak shipment rate of 0.93 million barrels per day. Commandeered barges also moved an average 1.3 Mb/d on the Mississippi. Surprisingly, the same need might arise even today, since there is still no crude-oil pipeline serving the East Coast refineries (New Jersey, Pennsylvania, Delaware), and an interruption of Atlantic or Gulf tanker traffic would shut them down. Only the Colonial

Pipeline System, with a capacity of approximately 2.1 million barrels per day, provides substantial capacity for importing refined products to the East Coast. Should that pipeline not operate, replacing its product flow (to say nothing of bringing crude to the East Coast refineries) would require the equivalent of more than 200 World War II T-2 tankers (16,000 dwt) on a continuous 13-day-round-trip shuttle between Galveston and New York--approximately the whole U.S. coastal tanker capacity, and enough to cause a monumental traffic jam in the ports [Stephens 1973:114].

- Facilities construction. Road shipment, though usually the most costly and energy-intensive, also generally offers the shortest construction times and the greatest topographic freedom of choice. Its infrastructure is also multi-purpose, not specialized to fuel supply like gas and power lines. Railway and waterway facilities are usually too costly for any but large users to buy them.

- Speed and joint shipment. In coal shipment, the cheapest method (barge) is also the slowest, least flexible, and most weather-vulnerable; the most flexible in routing (truck) is also the costliest; railways offer various compromises between flexibility and economy. All can keep different kinds of loads separated. So, surprisingly, can pipelines*, which can move their contents thousands of miles in a few days. Electricity moves instantaneously.

- Reversibility. Oil and gas transmission pipelines now in operation are generally unidirectional [Congressional Research Service 1977:I:14]. They can be reversed, and have been [id.:178,181], by modifying valves and compressors.

*For example [Congressional Research Service 1977:I:198-200], the Colonial Pipeline System, the largest and probably the most complex in the world, has three adjacent pipes, the largest having a diameter of 36" (91 cm), fed from ten source points and distributing to 281 marketing terminals. Thirty-one shippers dispatch 120 varieties of products to 56 receiving companies. In 1973, after an investment of over \$527 million since 1962, nearly 2000 miles of main pipe and over 1500 miles of lateral lines containing over 1 million tons of steel were being operated by fewer than 600 total employees; it took a product batch 12 days to move from Houston to Linden NJ, powered by 84 pumping stations (totalling 826,075 horsepower or over 600 MW) using over 2 GWe-h per year--enough to run for a month in 1973 all the houses in Louisiana, Georgia, Mississippi, and South Carolina. It took ten companies just to supply the valves for this extraordinarily complex engineering project [Stephens 1973:115]. The Colonial system accepts minimum batches of 75,000 barrels, occupying a 12-mile (19-km) length of pipe (an amount which takes an hour and a half to pass a fixed point), and separates them from adjacent batches of different composition by inflating between them a water-filled rubber "batching sphere" that fits the inside pipe diameter. Constant monitoring of the specific gravity of transmitted product enables operators to divert the "interface"--the small mixing zone formed by leakage around the batching sphere--into holding vessels for reseparation or blending into products of saleable purity. The order of batching is carefully defined to minimize contact between incompatible products, a full product sequence requiring ten days. For products more viscous than the higher-distillate heating oils, pipeline shipment is impractical.

Oil unit tank trains [id.:255] are even more easily reversible, requiring only appropriate loading/unloading equipment. Electrical grids are usually reversible without modification, subject to requirements of safety, metering, and stability (discussed below). In contrast, in the 1977 coal strike, Federal authority, though extensive (protecting coal distribution, requiring emergency electric interties, mandating allocations and sales of coal, etc.), did not extend to physically moving coal [Subcommittee on Energy & Power 1978:18], but most of the coal was not available to be moved anyhow because most power-plant coal depots had equipment only for unloading coal onto piles, not for reloading it for shipment to someplace else [id.:9].

2.1.8. Interactions between energy systems.

An energy system can fail because it does not receive external, auxiliary energy it needs in order to run. Gasoline pumps, for example, generally run on grid electricity. On the day an Amoco® gas station powered by an array of solar cells was being dedicated in 1980 in West Chicago, a violent thunderstorm cut off all power in the area, and the solar-powered station was the only one in operation [Energy Insider 1980:4]. (The American Petroleum Institute has published [Federal Emergency Management Agency 1979:22-23] an excellent guide to nine emergency methods of dispensing gasoline in a power failure, using motor vehicles, lawnmowers, bicycles, portable engines, or human muscles for motive power.) Electric power failures have often shut down sewage-treatment plants that were not powered by their own methane byproduct. Most municipal water plants require grid electricity to operate [Nevin 1969; Pickering 1969]; so, currently, do most oil refineries [Stephens 1970]. About half of U.S. domestic oil extraction depends on electrical supplies [Stephens 1973]. Except for the small fraction of U.S. coal carried in slurry pipelines, virtually all coal transportation depends on diesel fuel [Energy & Defense Project 1980:77], so a cutoff of imported oil "may threaten our supply lines for coal as well" [Congressional Research Service 1977:I:75]. Failure of power for dewatering pumps can flood coal mines so badly as to force their abandonment. All heavy machinery depends on a continuous supply of lubricants from the oil industry. Refineries need electrically pumped cooling water. Many power stations depend on diesel generators for safe shutdown and to run critical control and protective circuits if the stations and their grid supplies fail. Some fuels, too, are coproducts of others (natural gas liquids from natural gas processing, for example), and still others, like heating oil or propane, can become scarce if a shortage of, say, natural gas forces buyers to substitute [Federal Emergency

Management Agency 1979:1]. Interactions between different forms of energy supplies can leave even the homeowner stranded: most oil- or gas-fired furnaces need electricity to run their pumps and igniters. In short, any disturbance in the intricately interlinked web of fuel and power supplies can spread out in complex ripple effects at all levels, from primary supply to end-use, complicating substitutions and exacerbating the initial shortage.

Another worrisome interdependence of supposedly independent energy systems can arise from their colocation. Broken water mains can short out electric cables. A liquefied-gas tanker accident could destroy a power station or refinery. Fire and explosion can propagate between nearby pipelines or through a tank farm. Exploding gas mains can simultaneously disable electric and telephone cables located in the same tunnels under city streets. Early on 13 February 1981, an hour before rush-hour traffic, some 3 to 12 miles of Louisville's streets were instantly torn up by exploding sewers, apparently filled with hexane leaking from a factory a mile from the point of ignition [Marshall 1981]. Such an accident could easily knock out all under-street utilities at the same time. During the British conversion to North Sea gas, some public telephone booths started exploding: the higher gas pressure was too much for old joints, and the leaking gas entered adjacent telephone cable conduits and seeped up into the booths, ready for someone to walk in with a lit cigarette.

2.1.9. High capital intensity.

Capital intensity reflects resource intensity and thus indirectly measures the difficulty of building a system with limited resources. High capital intensity also has important operational, financial, and social consequences. Most modern energy supply systems are extremely capital intensive. Some, such as electric utility plant, are the most capital-intensive in the whole economy, with a capital/output ratio several times that of manufacturing industry. In general, synthetic-fuel and frontier (Arctic and offshore) oil and gas systems require about ten times as much capital per unit of capacity for delivering additional energy to final users as did the traditional direct-fuel systems (such as Appalachian coal, Texas oil, and Louisiana gas) on which the American economy was built. Central-electric systems, in turn, are about ten times more capital-intensive still [Lovins 1977b, 1978]. The resulting capital charges generally exceed the operating costs and profits that are the remaining components of energy price. Carrying charges for a plant costing, say, \$2 billion (such as a nominal 50,000 bbl/d synfuel plant) can easily exceed half a million dollars per day (\$6 per second), payable whether the plant runs or not.

This has several important consequences. First, the designers will be unable to afford much redundancy--major backup features that cost a lot but are seldom used. Second, there will be a strong temptation to skimp on downtime for routine maintenance--a temptation commonly indulged in reactor operations. A similar reluctance to shut down oil refineries for maintenance if they can be kept running without it means that minor leaks which in prior years would have been quickly fixed are now often allowed to continue for a year or more. The prevalence of known but unfixed leaks and other faults greatly increases both the likelihood of fire and the workers' exposure to toxins and suspected carcinogens. These economically motivated risks are a chief cause of refinery strikes by the Oil, Chemical and Atomic Workers' Union.

Another result of high capital intensity is limited ability to adapt to fluctuating demands. Quirk and Moriarty [1980:93] point out that the Natural Gas Policy Act of 1978, passed in the wake of the 1976-77 winter gas shortages and giving absolute priority to residential and small commercial users, may have a perverse effect. These users, who may not be interrupted, have the most temperature-sensitive demand, whereas industrial customers, who must be interrupted first, have the least. In a cold-weather gas shortage, a utility with many uninterruptible customers might reap windfall profits from unexpected extra sales, while a utility selling mainly to interruptible industrial customers might go into the red by losing sales needed to support unaltered capital charges. Profit-maximizing utilities may therefore seek to raise their proportion of uninterruptible, temperature-sensitive customers, thus increasing total national vulnerability to a cold-weather gas shortage.

The economic need for capital-intensive plants to run nearly continuously places a high premium on the correctness of engineering expectations that they will prove reliable. Technical mistakes, bad weather, external interference, etc. can produce massive economic penalties as well as disrupting energy supplies. For example, the financial fallout from the Three Mile Island accident --in terms of reduced bond ratings, higher cost of money, and the like--is proving more crippling to General Public Utilities than the direct costs of the cleanup or of buying replacement power. High capital intensity also commonly reflects a degree of complexity that hampers diagnoses and repair of faults and limits available stocks of costly spare parts (section 2.3). The corresponding managerial complexity places additional stress on another scarce resource, especially scarce in emergencies--the attention of gifted managers.

2.1.10. Long lead times.

The time it takes to build a major energy facility--of the order of a decade, or irreducibly perhaps half that--contributes to its capital cost and investment risk. It requires foreknowledge of demand, technological and political conditions, and costs further into the future, when forecasts are bound to be more uncertain. This uncertainty imposes a severe financial penalty on bad guesses, especially overconstruction--a diseconomy of scale considered further in Chapter 5. Frequently, long lead times require major facilities to be built, or at least their designs frozen, before significant operating experience is gained with their evolutionary predecessors. This tendency to run ahead of sound engineering experience tends to encourage costly mistakes which may seriously affect long-term energy supplies.

Long lead times also create risk even if forecasting is perfect. This is because people considering in 1981 a billion-dollar commitment to a plant that cannot be finished until 1991 and must then operate into, say, the 2020s want to know with confidence the conditions of finance, regulation, and demand throughout this period. But they want this certainty in a society whose values and institutions are in rapid flux--a society that changes its politicians every few years. If democracies are to retain their flexibility and adaptiveness, they must remain free to change their minds. This is not a problem of accurate forecasting but of maintaining political degrees of freedom essential to our concept of governance. It means that the certainty desired by the promoters simply cannot be given. This tension--perhaps a fundamental incompatibility between the characteristics of many modern industrial investments and those of a pluralistic political system in a changing world--is bound to express itself somehow, and is an inherent source of vulnerability in these facilities or in the adaptability of our institutions or both.

2.1.11. Specialized labor and control requirements.

Modern society is becoming disturbingly dependent on skills possessed by small numbers of highly organized people. Air traffic controllers, for example, are virtually irreplaceable, at least on short notice. A 24-hour strike by 1500 controllers and allied staff (presumably 500 per shift) recently did what Hitler was unable to do--close British airspace [Los Angeles Times 1981b]. Likewise, modern systems for the continuous bulk delivery of energy are exceedingly complex and require meticulous automatic and manual control which is understood and can be run and maintained by only a few highly trained specialists. Railway loading operations are almost unique in having so far largely resisted automation, retaining human judgment instead of computerization [Congressional Research Service 1977:I:267]; gas and oil pipelines and

electric grids are already almost completely computerized. This is indeed essential because of their complexity.

An oil pipeline, for example, needs several dispatchers, but they could not unaided keep track of the status of pumps, valves, flow rates, batch locations, schedules, metering, costs, etc. (Just a 3°F change, for example, in the temperature of the entire 36" Colonial pipeline, or a 150 lb/in² pressure change, would change its volume by some 10,000 barrels worth several hundred thousand dollars [id.:200-201].) Stephens [1973:34] remarks that in one major pipeline system, "One small room, in a large southern city, houses the complete...control system [for]...several states....Forced entry to the computerized center [and low-technology sabotage]...could suddenly put the entire system back on hand operation. Each control valve, of many hundreds, would have to be visited, but now only a few men are available to run the system. There are no repair crews except contract crews in most cases." The Plantation and Colonial pipelines, supplying most of the Eastern Seaboard's refined products, not only parallel each other and interconnect at many vulnerable points; the control systems for both are in the same building. "A repeat of the University of Wisconsin action by saboteurs could do serious damage to these operations" [id.:114]. (Colonial has installed a backup control center.)

Perhaps most dependent on control automation are electric grids, where transient events such as lightning bolts or routine circuit interruptions often require actions within hundredths of a second to prevent damage. Giving effect to control decisions throughout the far-flung grids of wires and pipelines requires complete dependence, therefore, on computer decisions not first checked by human judgment, and on electronic telecommunications links--a dependence whose disturbing consequences are explored in later sections.

The specialized nature of the control systems, and of maintenance operations needed to maintain both them and the devices they control, concentrates immense power in few hands. The economic and social cost of energy disruption, let alone the direct financial damage incurred by carrying charges on idle equipment, place "power to the people" in the hands of very small numbers of people well aware of that power. As an official of the British power workers' union remarked shortly after a coal strike had brought down the Heath Government in 1974, "The miners brought the country to its knees in eight weeks; we could do it in eight minutes." His colleagues have since repeatedly threatened national blackouts as a prelude to negotiations for various desired concessions, including (in one recent instance) basic wages of up to \$50,000 per year [Daily Mail 1979]*. Ironically, the Conservative Government's well-known desire to reduce vulnerability to future coal-miners' strikes by substituting nuclear power would increase vulnerability to disruption by even more specialized and *Israeli power workers, as we write this, are gradually blacking out the country [Los Angeles Times 1981n].

nearly as militant workers in power plants and power dispatching centers. Electrical supplies have also become a bargaining chip in Australia [Straits Times 1980] and elsewhere, as have water supplies, sewage treatment, and other utilities essential to public health and safety. However responsibly a union or management able to control such key utilities may behave, the very possibility of disruption tends to foster suspicion and intolerance if not worse, further increasing the social tensions which themselves contribute to the risk.

2.1.12. Adaptability of fuel distribution systems to other materials.

Virtually all analyses have considered the vulnerability of energy systems only to interruptions of supply. Many systems can, however, be interfered with in other ways at least as damaging--large-scale versions of putting sugar in a gasoline tank. A few examples make the point:

- It would probably not be difficult to introduce a foreign substance into crude oil being stored or pipelined to many refineries. Such substances might include radiotoxins which will neither affect nor be affected by processing but would be widely dispersed by subsequent burning of the refined products. Like a suspicion of botulism in canned foods, they could make substantial amounts of petroleum products unfit for use (or, for that matter, for destruction by conventional means), and could be an effective means of extortion. Alternatively, certain substances could be introduced which are potent poisons of refinery cracking catalysts. Since most cracking catalysts are in fluidized rather than fixed beds, with a residence time of order seconds, poisoning them has mainly a nuisance value, requiring more catalyst to be replaced. Before crudes are hydrocracked, they also go through a demetallizing stage to remove most of the nitrogen, sulfur, nickel, and vanadium, and this stage uses relatively poison-resistant catalysts. Poisoning the very large volumes of oil in pipelines or storage to a level sufficient to interfere seriously with refining would in any event require large amounts of contaminant, as the catalysts are not as sensitive to heavy- or alkali-metal poisons as (say) photographic emulsions are to mercury. Nonetheless, there are some special circumstances in which this type of potential interference is worth considering.

- The national grid of natural-gas pipelines--over a million miles for transmission and distribution--offers an inviting route for dispersing unpleasant materials. In early 1981, the Environmental Protection Agency found that natural gas systems in Southern California, Chicago, and Long Island had become accidentally contaminated with liquid PCBs (polychlorinated biphenyls), an extremely persistent and toxic liquid whose manufacture was banned in the U.S. in 1976 but which is still widely used in transformers, capacitors, etc.

[Billiter 1981]]. Not only retail distribution systems but also some segments of interstate pipelines and their gate stations were contaminated. EPA thinks the PCBs may have entered the gas lines as a pump or compressor lubricant many years ago, perhaps via leaky seals. The PCBs detected in retail customers' meters are not so far believed to mean that burning the gas had actually released significant amounts of PCBs indoors. Nonetheless, there are cheap, very disagreeable substances which could be deliberately introduced in bulk into the national gas grid from any of thousands of loosely supervised access points. Such substances could be widely distributed and released before likely detection. Some could contaminate the inside of the pipelines--the third largest fixed asset in all American industry--so as to make them very difficult to clean up. Whether a major public hazard could be caused in this way would require further analysis at an indiscreet level of specificity; but it appears there is, at a minimum, a potential for causing public anxiety and disruption.

- Another category of potential threats might involve the fuel distribution system or local storage tanks. Apparently some organisms promote the gelling of liquid oil; others have been developed to eat oil slicks at sea. It may become possible for self-reproducing organisms of either kind to become a threat, accidentally or deliberately, to oil storage and processing systems*. It is hard to say whether this would be easy or difficult, and it may seem far-fetched; but strikingly effective instances of biological sabotage are already known, ranging from releasing moths in a cinema to sowing spores of certain mushrooms which, on sprouting, hydraulically fracture any concrete that has meanwhile been poured over them. The adaptability of organisms and the ingenuity of some amateur biologists suggest that biological threats cannot be discounted. Already, such accidental infestations as Mediterranean fruitfly, Corbicula in power plants (Ch. 1.2.1), kudzu on much Southern land, and water hyacinths on waterways suggest a considerable potential for mischief.

- Finally, an analogous problem may exist with electricity, because as much harm can be caused by increasing as by interrupting its supply. Some manipulations of electrical control systems may be able to increase grid voltages to levels which damage not only generating and transmission equipment but also widely dispersed distribution and end-use equipment. This has already happened by accident, as in restoration after the July 1977 New York blackout described in the following section. Alternatively, persistent low voltage or operation of only one of several phases on multiphase lines can cause epidemics of burned-out motors and other equipment over a wide area: Stephens [1970:149] notes an oilfield operation that lost 153 motors in one evening in this way. Repairing such widespread damage to end-use devices can be extremely slow and

*Oil stored in South African gold mines was reportedly gelled by fungi and bacteria, making it very hard to ex-extract [ERAB 1980:65]. Some refined products can be stored for only a few months to years unless stabilized by special additives [Davis 1981]; presumably destabilizing additives also exist.

costly. As noted below (Chapters 2.2.3 and 3.2.3), analogous interference with gas distribution pressures can endanger large numbers of end-users simultaneously, even on the scale of an entire city.

2.2. Graceful Versus Catastrophic Failure in Energy Systems

The previous section has identified some elements of modern energy systems that make them vulnerable to the threats noted in Chapter 1. But such a catalogue cannot capture the interactive vulnerability of a whole energy system. This section therefore examines several case-studies of ungainly failure, and some of energy systems that failed with grace.

2.2.1. The 13-14 July 1977 New York City blackout.

The failure of the 60-Hz electric power grid in New York in July 1977 was not the first or the largest to occur there. In 1965, a cascading power failure originating in a malfunctioning relay in Canada interrupted the electrical supply of most of the Northeastern United States. Some thirty million people were blacked out for anywhere from one to 13-1/2 hours. A load totalling 43.6 GWe--23% of 1965 U.S. peak demand or 18% of 1965 installed generating capacity --was lost [Federal Power Commission 1977:26]. On 13 July 1977, three days after the Chairman of Consolidated Edison Co. of New York had said he could "guarantee" that a recurrence was remote [Congressional Research Service 1979:142], nearly nine million people were blacked out for 5-25 hours through "a combination of natural events [lightning], equipment malfunctions, questionable system design features, and operating errors" coupled with serious lack of preparation to use available facilities to prevent complete failure [Federal Energy Regulatory Commission 1978:1].

Geography and operational circumstances contributed to the 1977 blackout. The New York City grid relies heavily on imports of bulk power in a narrow corridor from the north, where power is available at relatively low cost and can be delivered overland without requiring expensive underwater cables. This clustering of lines increases vulnerability to storms and sabotage. There are some interconnections in other directions, but in July 1977, one key link was inoperable because a phase-regulating transformer, after causing several earlier local power failures, had failed beyond repair ten months earlier (it eventually took over a year to replace [Subcommittee on Energy & Power 1977:34,149-154;1978a:44,95]). Three generating plants on the Con Ed system were also down for repair: the Indian Point 2 nuclear plant (873 MWe), with a failed pump

seal; Bowline Point #2 (601 MWe), with a boiler problem; and Astoria #1 (775 MWe), with a turbine failure. Within the Con Ed area, therefore, only 3.9 GWe was being generated to serve a load of 6.1 GWe, and the rest was being imported through six interties. It is the successive failure of these transmission systems, and their interaction with local generators, that led to the system failure. There was plenty of generating capacity available in the "pool" of adjacent utilities with which Con Ed was interconnected, but by the late evening of 13 July 1977, there was no way to deliver that power to the city.

Perhaps the best description of the failure sequence is by Boffey [1978]:

The trouble began...when lightning struck a[n imperfectly grounded transmission-line] tower in northern Westchester County and short-circuited two 345-kilovolt lines....[P]rotective relays...triggered circuit breakers to open at both ends of the affected lines, thus isolating the problem from the rest of the system. This is exactly what the circuit breakers are supposed to do. However, they are also supposed to reclose automatically once the fault dissipates, and this they failed to do. One transmission line failed because of a loose locking nut [which released air pressure from a circuit breaker: Clapp 1978:10]...; the other because a reclosing circuit had been disconnected and not yet replaced....

Two other facilities also tripped out of service....A nuclear reactor [Indian Point 3] shut down automatically when the circuit breaker that opened to contain the lightning fault also [by a design fault] deprived the reactor of any outlet for its power....[A]nother 345-kilovolt line--a major tie across the Hudson--tripped out because a protective timing device was designed improperly....Thus, in one stroke of misfortune, Con Ed lost three major transmission lines and its most heavily loaded generator.

Even so, Con Ed regained its equilibrium by importing more power on the remaining tie lines and by increasing its own generation somewhat [but did not restore a safety margin]....Then lightning struck again...and short-circuited two more 345-kilovolt lines. Again there was a malfunction. One line reclosed automatically [but]...the other remained open because a relay had been set primarily to protect a nuclear reactor (which, ironically, was out of service) rather than to facilitate reclosing of the line....The loss of the line...caused a temporary power surge that tripped out another 345-kilovolt line. This should not have happened but did, because of a bent contact on a relay.

Con Ed's control room succumbed to confusion and panic....[The] system operator [assumed]...a particular transmission line was still in service [and]...failed to read a teletype [saying it was down]....Moreover, because of Con Ed's antiquated control room layout, he was unable to see a more dramatic indicator in another room--a flashing screen with a high-pitched alarm. The personnel there knew the line was out but failed to tell him....[H]e ignored [seven]...suggestions from the power pool that he shed load. Then, as the situation deteriorated, he...dumped his...responsibility on his boss, the chief system operator, who sat at home in the dark reading diagrams by a kerosene lantern and issuing orders over the phone....The chief ordered voltage reductions--but these were too little and too late. Eventually he also ordered that a block of customers be disconnected. Whereupon the confused operator [rendered the load-shedding control panel inoperable by apparently turning]...a master switch the wrong way.

The performance of Con Ed's generators was equally erratic. Con Ed's system operator delayed 8 minutes...before requesting a fast load pickup

from generators that were supposedly able to respond in 10 minutes. He [then] got only half the power he expected--and only 30% of what Con Ed had incorrectly told the power pool it could provide. Some equipment malfunctioned; other units were undergoing routine inspection but had not been removed from the fast-start capability list; some were not even manned. [All the night-shift operators had been sent home, and the remote-start capability had been removed some years earlier: Subcommittee on Energy & Power 1977:32,100-101. At most 55% of Con Ed's total in-city generating capacity was actually operable: id. 1978:53.] Similarly, when Con Ed sounded the maximum generation alarm some 10 minutes after the second lightning strike, it again failed to get the anticipated response from its 30-minute reserve generators.

As the system cascaded toward collapse, heavy overloads caused the failure or deliberate disconnection of all remaining ties to neighboring utilities. Con Ed['s]...last hope was an automatic load shedding system that had been installed after the 1965 blackout. [It] worked beautifully to disconnect customers....But it also unexpectedly caused a rapid rise in system voltage that caused a major generator to shut down....The remaining generators could not restore equilibrium. Eventually, protective relays shut them down to prevent damage...[and] the city was blacked out.

Nearly twelve weeks later, on 26 September 1977, another thunderstorm tripped four transmission lines with six lightning bolts. Automatic reclosing equipment again failed to perform, shutting down 40% of Con Ed's generation. Only a more alert operator response in shedding Westchester loads prevented a second, more serious blackout from spreading again across the city. On that occasion, the equipment failures included an out-of-service instrumentation channel at Indian Point 3 [Clapp 1978:22], a wiring error in a relay [:23], deactivation of a reclosing circuit by the unexplained placing of a switch in the wrong position [:23], and a defective relay [:25]. Like earlier equipment faults, these resulted from "serious failures in inspection and testing" [:39]. Though local trip systems prevented in 1977 most of the serious damage that the 1965 blackout had caused to 1.5 GWe of generating equipment [Joint Committee on Defense Production 1977a:23], many of the underfrequency relays meant to shed load automatically in 1977 did not initially operate.

Serious, multiple operator errors, reminiscent of those identified in the Three Mile Island accident by the Kemeny and Rogovin reports, also dominated the July 1977 blackout. Many of the training and procedural problems had already been identified in the 1965 blackout [Subcommittee on Energy & Power 1977:53-65] but not fixed. Lack of unambiguous linguistic conventions like those used in air traffic control contributed to the confusion [Federal Energy Regulatory Commission 1978:139]: different operators concealed their meaning from each other and, on occasion, from themselves. The system operator was apparently hard of hearing anyway [Subcommittee on Energy & Power 1977:46], perhaps contributing to his poor performance in communicating over the telephone from a noisy and doubtless chaotic control room.

Three technical features of the 1977 blackout deserve special attention. First, it was of a character unforeseen in any official design criteria. The State's investigator concluded: "The inability to achieve stable isolated operation [i.e. without interties to adjacent areas] stems from a general failure to think through the problems that transmission losses can create. For example, virtually no planning consideration has been given to the generation reserves needed in the event of transmission losses. Installed generation reserve capacity is determined solely with reference to potential generation shortages. Similarly, the Pool's minimum operating reserve criterion...is designed to meet generation shortages, not transmission losses [, and...] assumes sufficient transmission exists to deliver the members'...reserve capacity to the system suffering the shortage. Where disturbances on the bulk transmission system severely limit the ability to transfer power, the Pool's existing reserve requirements are inadequate." [Clapp 1978:59-60] This had already been clearly noted in the 1965 Federal Power Commission report to President Johnson--"Cascading power failures are usually the result of insufficient capability within...transmission links"--but neither Con Ed nor Pool criteria followed the logic. The reason Con Ed had not realized that load shedding would produce overvoltage and trip the Big Allis generator at Ravenswood was that they had simply never analyzed the behavior of an isolated Con Ed system [Boffey 1978:995]*.

Second, the July 1977 power failure produced unexpected secondary consequences that seriously hampered recovery. There was inadequate light and power for troubleshooting or manually operating major substations [Joint Committee on Defense Production 1977a:5]. Auxiliary equipment at power stations--lubricating and cooling pumps, boiler feedwater pumps, etc.--failed gradually with declining voltage, compromising and in some cases modestly damaging major equipment [Federal Energy Regulatory Commission 1978:49]. Assessment of the status of equipment, and coordination of early restoration efforts, was also hampered by the complete failure of Con Ed's UHF and VHF radio networks. The main repeater had two power sources; one had failed before the blackout and the other failed to start. The backup power supply to the backup repeater station also failed to operate. This triple failure also exposed shortcomings in radiotelephones and direct telephone lines. The backup radio repeater was not repowered until another emergency power source could be hooked up two and a half hours later [id.:45].

Most dismaying was the unexpectedly rapid loss of pressure in oil needed to insulate and cool the main high-voltage underground power cables. After the 1965 blackout, standby generators had been provided to operate generator lubri-

*The isolation of St. Louis on 13 February 1978 was also a surprise [NERC 1979: 13-14], but resulted in overfrequency and caused no loss of load.

cating pumps and other key protective equipment in power stations. The Federal Power Commission had then recommended installing standby power for pumping oil to the underground cables too--as Commonwealth Edison Co. had done, for less than half a million dollars, in the underground Chicago cable system. Apparently Con Ed was unaware of this recommendation. That cost them at least five hours in recovery time in 1977 [Subcommittee on Energy & Power 1977:26-27]. They had thought the cables would hold oil pressure for 4-6 hours [Subcommittee on Energy & Power 1978a:139], but pressure actually decayed much faster. This caused many short-circuits and some equipment damage, causing further delays which lost more oil pressure. Finally it was necessary to bring in portable generators to run the oil pumps, restore all oil pressure throughout the length of the cables, and monitor pressure at all terminations and connections before the cables could be safely re-energized [Federal Power Commission 1977:20,46].

Third, the July 1977 Con Ed blackout illustrated some general features of large (and especially of urban) electric grids that make their operation more difficult to sustain in emergencies. These can be better understood by reference to what happens when power flows in a grid are interrupted.

Sudden trips (disconnections) of elements of power systems occur commonly in the midst of normal operation. If lightning short-circuits a transmission line, for example, automatic circuit breakers open, then attempt to reclose in a fraction of a second and again in several seconds if at first unsuccessful. Users are aware only of a brief flickering of the lights if all goes well. If, however, the fault has not cleared (or the breaker does not work properly), the breaker will remain open. If an alternative transmission path is available (as it normally is), the electrical flow redistributes itself within a few cycles. This may overload other lines. They can tolerate substantial overloads for short periods without overheating, and can even be run for up to four hours at their "long-time emergency rating" without damage, but before time-and-temperature limits on the lines are reached, operators must reroute power or shed loads to bring the lines within safe limits. Similar readjustments may also be needed after the initial rapid redistribution of power flows that accompany the sudden trip of a loaded generator. Further, the generator itself must rapidly bypass steam from its turbine in order to avoid serious damage from spinning too fast without load. Thereafter the turbogenerator cannot be rapidly reconnected to the grid, but must be brought up gradually from almost zero load [Federal Energy Regulatory Commission 1978:15-16].

In practice, the detailed electrical phenomena occurring when normal bulk power flows are interrupted are very complex and demand elaborate mathematical analysis. One kind of potentially damaging aberration is rapid transients of

voltage or current [id.]: "[A] stiff mechanical structure [which]...receives a shock at one point...may be damaged by [a propagating wave of] stress appearing far from the point of the original shock...[depending] on the form of the structure and the relative stiffness and strength of its members." Electrical networks have analogous elements and properties. Transient surges of high voltage can break down insulation in a cable or transformer, thereby causing a secondary fault. A current surge can likewise trip a protective breaker and needlessly disconnect a circuit. The electrical properties of long transmission lines and (especially) of long underground cables tend to enhance transients.

Alternating-current power grids can also become unstable by losing their synchronization. "In normal operation, all of the [generator] rotors...are rotating in precise synchronism. Further, the power output and other electrical quantities associated with each generator are absolutely dependent on this synchronous operation. If a generator is subjected to a sufficiently large disturbance,...as...from a nearby fault, it may...'pull out' of synchronism, even though the original disturbance is momentary. Once synchronism is lost, the power output of the unit drops rapidly" [id.:16-17] and it must immediately be taken offline until ready for exact resynchronization.

If a power grid is more than momentarily subjected to a load larger than it can sustainably supply, and if "spinning reserve" capacity already synchronized with the grid cannot be brought into full production to make good the deficit, the operating generators will slow down at a rate that depends on their "inertia constant" (ratio of stored angular momentum to output rating) and on the extent to which the change in line frequency changes the load [id.: 37]. The frequency of the whole interconnected system is thus pulled down below the normal 60 Hz. This can cause more power to flow toward the deficit area, perhaps further overloading transmission lines [id.:17] and probably tripping protective breakers. If protective devices do not work properly, different elements of a grid may try to operate at significantly different frequencies, "bucking" each other. This causes enormous internal stresses and, probably, serious damage. Some modern turbogenerators of very large capacity (well over 1 GWe in a single unit) work so close to the yield limits of their materials that they have little safety margin for the stresses generated by loss of synchronization: some will reportedly suffer gross mechanical failure (e.g. by the shaft's flying apart) if the frequency deviates by one or two percent while they are under full load.

Transmission lines, because of their electrical properties, are subject to two kinds of limits on how much power they can safely handle: thermal limits, set by their ability to dissipate heat to their surroundings without sagging,

and system stability limits. "Transfer of power at a given voltage can be increased only up to a certain level beyond which it becomes impossible to maintain synchronous operation between generators at the...ends [of the line]Following a disturbance, it is possible for a machine to operate momentarily past the stability limit and then to regain synchronism..., but this ability is limited and operating conditions are established to maintain operation within safe limits allowing for the occurrence of some disturbances." [Econ. Regul. Administr. 1981:1:2-5] These limits become more stringent at higher voltages and with longer lines--both characteristic of the trend towards larger, more remotely sited generating plants.

One form of this problem was illustrated in microcosm in the New York blackout. Underground cables, used throughout Con Ed's area, have large distributed capacitance (ability to store an electric charge between two separated conductors). This capacitance could produce large voltage transients if not compensated by series inductances (conductors which store energy in their magnetic field; like capacitors, inductances display "reactance," or ability to resist changes in the direction of flow of an alternating electric current). Con Ed's "black-start" procedures (i.e. for restoring the grid after complete power failure) relied on the windings of baseload generators for about two-thirds of the needed inductive reactance, but none of it was initially available for compensation, and inductive compensation in another critical circuit was unusably damaged [Federal Energy Regulatory Commission 1978:47-48]. Efforts to restore the grid rapidly in large sections apparently led to series resonance effects (electrical oscillations) between the unbalanced inductive and capacitive elements, causing high-voltage transients that damaged cables, transformers, and switchgear [id]. Indeed, the tripping of the 844-MWe Ravenswood #3 generator was caused by cable capacitance too: when load-shedding removed large inductive loads (motors) which had previously compensated for the cable capacitance, the capacitive surge raises voltages to as much as 11.5% above normal, and the resulting pathological voltage-current relationships confused the generator's controls so much that it shut off in self-protection. This sealed the fate of the Con Ed grid by dropping system frequency from 60 to 57.8 Hz--a level low enough to be sustained by available generating capacity (automatic load-shedding already having occurred), but too low to keep power-plant auxiliaries (fuel pumps, draft fans, feedwater pumps, etc.) running fast enough to support the 33 generators still operating*. The resulting vicious circle of plant failures and further declining frequency crashed the grid in four minutes [id.:37-38, Clapp 1978:17].

*The isolated Israeli grid could have tolerated a drop of at least 5%, equivalent to 57.0 Hz: it uses three layers of under- and over-frequency relays to shed and restore loads, achieving perhaps the world's highest load factor. The Eastern European grids are similarly frequency-labile; Western European, about five times less so; North American, about five times less so again.

These stability problems are not unique to New York's cable system; in various forms they are emerging nationally. In 1976, the Assistant Director for Systems Management and Structuring in the U.S. Energy Research and Development Administration [Fink 1976] stated:

It is becoming apparent that the increasing complexities of the nation's electric energy system are rapidly outstripping its capabilities. Our interconnected electric energy systems seem to be evolving into a new condition wherein "more" is turning out to be "different." As they become more tightly interconnected over larger regions, systems problems are emerging which neither are presaged, predicted, or addressed by classical electrical engineering and which are no longer amenable to ad hoc solution.

Up until the past decade the ability of an electrical system to ride out a severe electrical disturbance (i.e. to maintain stability) could be evaluated on the basis of its ability to remain stable through the first rotor angle swing (about one second) following the disturbance. It is now recognized, however, that this condition is no longer sufficient. Instances have occurred wherein systems survived for several swings following a disturbance before coming unstable due to a lower frequency phenomenon.

Accordingly, the industry has been devoting considerable effort to... studying what has become known as the dynamic stability problem...[and] it is acknowledged that the larger, more tightly interconnected system is behaving in a fashion qualitatively different from that of earlier smaller systems.

A systems problem which was not predicted...but which has rapidly become the focus of much...attention is...subsynchronous resonance. [It was]...standard practice [to install] series capacitors to compensate for the inherent inductance of very long lines [i.e. the reverse of Con Ed's requirements]. When this was done in the case of some lines out west, the resonant frequency of the series capacitor-inductance combination was close enough to the natural frequency of the shafts of the units involved to set up mechanical vibrations which resulted in shaft failure. The phenomenon is amenable to analysis by available theory, but the necessary tools were not readily available and the problems were not anticipated.

As an example of a future, potentially important problem outside the scope of classical electrical engineering, we point to the fundamental problem of information transfer and decision making in the case of multiple independent control centers, whose decisions affect primarily their own portions of a common interconnected system. In actuality the action taken by any one such center affects the whole....[A]nalyzing... effective control strategies...is in its infancy.***

Today's electric energy system in the United States is one of the most complex technical systems in existence. Unlike most other industries, the individual components do not operate independently but are tied together in an interacting system covering most of the continental United States, wherein deliberate or inadvertent control actions taken at one location can within seconds affect the operation of plants and users hundreds of miles distant....[T]he introduction of complex new technologies into the existing, already-complex system [and the need to consider tighter fiscal and environmental constraints compound]...the complexity of the system.

The point of all this is that there does not yet exist any comprehensive applicable body of theory which can provide guidance to engineers responsible for the design of systems as complex as those which will be required beyond the next generation....[T]here will be...problems of great importance which will be quite different from today's problems, and the conceptual tools and underlying theory required for their effective solution have not yet been developed.

In short, there is a good deal about the operation of modern large-scale power grids that able engineers are hard pressed to anticipate even in normal operation. In abnormal operation, as Con Ed found, their complexity can be sufficient to defy a priori analysis. This is in itself a source of vulnerability to mistakes, failures, and malice. We may well find, as power systems evolve in the present direction, that they have passed unexpectedly far beyond our ability to foresee and forestall their failures.

2.2.2. Military vulnerability.

Even when energy systems were considerably simpler than modern electrical grids, they proved attractive targets in wartime. The Energy and Defense Project [1980:19-29] has found several such cases instructive. Hitler's Germany used electricity for three-fourths of industrial motive power, as well as for all electrochemical processes (arc furnaces, electrolysis, production of synthetic nitrogen and oil and rubber). Four-fifths of the electricity came from central thermal plants. These were highly concentrated: in 1933, 1.4% of the thermal plants provided over half the total output, and 5% provided four-fifths of the output. The Allies, however, assumed that despite this inviting concentration, German grid interconnections provided enough flexibility of routing that power stations did not deserve a high priority as bombing targets, and indeed this was not done on a large scale until the vast bombing raids of 1944. The Nazis were delighted: they felt, and responsible officials including Goering and Speer said afterwards, that systematic targeting of power plants would have curtailed the war, perhaps by two years, and that they could not understand why the Allies had passed up such an efficacious opportunity. Seemingly confirming these German fears, synthetic oil production, which by early 1944 accounted for over half the German oil supply, was crippled by selective bombing in just a few months, bringing much of the Nazi war machine to a halt.

In striking contrast to this centralized vulnerability, Japanese electrical production in World War II [*id.*] was relatively decentralized: 78% came from small, highly dispersed hydroelectric plants that were not individually attractive targets, and the largest single dam supplied less than 3% of national electricity. The more centralized thermal plants, though they provided only 22% of the total electricity, were so comparatively vulnerable to urban bombing raids that they sustained 99.7% of the damage.

This lesson was not lost on Allied analysts: the centralized hydroelectric dams on the Yalu River became a key target in the Korean War. At least since then, if not for longer, the People's Republic of China has reportedly taken military vulnerability to heart in dispersing energy facilities (e.g. most of

rural China's electricity comes from several GWe of microhydro sets, often of a few kWe each [Lovins 1978:495], and small biogas plants provide extensive fuel for cooking and lighting). A similar philosophy is reportedly applied, so far as practicable, in Israel--especially after Israeli jets destroyed virtually the whole of Syria's oil installations in a half-hour early in the Six Days' War because they were all in one place. Rhodesia made the same mistake--centralized oil depots--and paid for it (p.78) when black nationalist guerrillas blew one up in December 1978. Likewise, June 1980 opened with a strong attack on the SASOL synthetic-fuel plants that provide much of South Africa's liquid fuel. Similar attacks have become more common in guerrilla wars since Egyptian saboteurs burned British oilfields in Libya in 1956 [de Leon et al. 1978:22]: at this writing, guerrillas are said to be closing in on dams and power plants in such countries as Chile and Angola. On 14 June 1978, Red Brigades terrorists caused \$600,000 worth of damage and blacked out part of the city for several hours with a series of bombs in a power station [Tanner 1978]. Accident or sabotage in a San Juan power plant blacked out Puerto Rico on 10 April 1980, shortly after the plant's chief engineer was kidnapped [Anchorage Times 1980; New York Times 1980d]. San Salvador was blacked out 6 February 1981 by a power-plant bombing--the fourth attack on power installations in four days [Atlanta Journal & Constitution 1981]; by 20 March, guerrillas were reportedly surrounding a dam providing half El Salvador's electricity [Los Angeles Times 1981m].

The French military establishment is reported [Caputo 1980:42] to wish to reduce vulnerability by decentralizing the energy system--a desire doubtless heightened by the "impossible" cascading failure of virtually the the entire French electric grid on 19 December 1978, with lost production officially estimated at nearly \$1 billion [New York Times 1978, 1978a; Le Monde 1978, 1978a]. Even in the Soviet Union--where central electrification has been a sacred tenet of the Communist Party since Lenin declared Communism to consist of 'collectives plus electrification'--there is "reportedly a standing argument between the Soviet military and the Politburo....The military argues that decentralized energy systems are of primary importance for civil defense and therefore essential to Soviet national security. The Politburo insists on centralization of primary energy systems in order to ensure party control, and is apparently prepared to risk a significant degree of national security to do so." [Holmberg 1981]

2.2.3. Surviving grid failures.

Centralized supply grids cannot discriminate well between users. Electricity for a water heater, which may be unaffected by a few hours' interruption,

must bear the high cost of the extreme reliability required for subways and hospital operating theaters. A degree of individual matching of reliability between source and need can save a lot of money, as noted in Chapter 7. Moreover, the grid is all-or-nothing: it must be so reliable because its failure is so catastrophic, instantaneously affecting a wide area. If your oil furnace breaks down, you can put on a sweater or go next door, but if the electric grid fails, there is no next door: everyone is in the same boat.

Electrical grids, as Con Ed's experience testifies, can fail catastrophically. So can pipeline grids. Both expose large flows of energy to lasting and instantaneous disruption by single acts, with only limited freedom to re-route. But while electrical grids can transmit power (provided it is properly synchronized) at levels varying all the way to zero, gas pipelines cannot: the pumps fail if gas pressure falls below a certain level. In practice, this means that gas grids must keep input in step with output. If coal barges or oil tankers cannot deliver fast enough to keep up with demand, there is simply a shortage at the delivery end. But if a gas grid cannot pump fast enough to keep up with demand, it can cease working altogether. In January 1977, calling on stored gas and adding grid interconnections was not enough to keep up the grid pressure, so major industrial customers had to be cut off, causing severe dislocations in Ohio and New York. But the alternative would have been even worse, because pressure collapse could not have been confined to the transmission pipelines. Without abundant high-pressure gas being supplied continuously, the gas distribution system too would have been drained below its own critical pressure. If distribution pressure collapses, pilot lights go out in innumerable buildings (including those not currently occupied), requiring a veritable army of trained people to go immediately into each one, turn off the gas to prevent explosions, and later return to restore service and relight the pilots. This occasionally happens on a local level, but has hardly ever happened on a large scale (Paris in 1944 might be an instance). It is such a monumental headache that gas companies strive to avoid it at all costs [Kalisch 1979]; indeed, the gas industry generally considers it an abstract problem--much as the electric power industry considered a regional blackout until 1965. Yet, ominously, an extortionist threatened a few years ago to cause a brief interruption in Philadelphia's gas supply--long enough to extinguish the pilot lights, but short enough to cause instant and widespread "urban reversion" shortly thereafter.

Such vulnerability to large-scale system-wide failure with catastrophic consequences is clearly not a desirable feature for any energy system. But it is not inevitable: alternative distribution patterns can make such failures

impossible. While Ohio and New York factories and schools were shut down in the gas shortages of early 1977 to prevent a wider collapse of grid pressures, gas use in equally chilly rural New England, in striking contrast, was virtually unaffected--especially in Vermont, the contiguous state least served by pipeline gas. The difference was that rural New Englanders had always used bottled gas. System-wide failures with loss of pumping pressure or pilot lights could not occur. Not everyone ran out at once, so neighbors could help each other through spot shortages.

In previous gas shortages, too, the same overstressed supplies of natural gas and of natural gas liquids had caused disruptions in other areas but not in northern New England with its decentralized, unsynchronized pattern of gas delivery and use. It is true that bottled gas comes from remote sources and that its distribution is liable to disruption; in the Ohio River Valley in early 1977, rural deliveries on poorly cleared and maintained roads could not always be maintained even though "extra propane trucks were sought across the Nation" and "Every available LPG rail car was purchased or leased" [Congressional Research Service 1977:III:190]. But from the end-users' point of view, shortage in one building, and at a fairly predictable time, is vastly preferable to simultaneous area-wide failures without warning. This capacity is also considered an important preparedness measure by some Israeli planners: in 1975, although there was no gas pipeline service in Israel, some 96% of homes had gas service--from bottles--whose independent, highly dispersed storage was virtually undisruptable.

Another incident shows the value of independent local supplies which, like the solar cells that powered the Chicago gas station, can stand alone at need, even though in normal operation they need not forego the advantages of grid interconnection. In Finland several years ago, a general strike shut down much of the national electrical grid. In the industrial city of Jyväskylä, however, the local combined-heat-and-power station (a common fixture in Scandinavia) was able to disconnect from the grid and keep the city powered in isolation. The money saved by not having to shut down the local factories for the duration of the strike reportedly paid off the capital cost of the power plant immediately, greatly impressing city officials with the resilience achieved by such simple means. This feature will be further considered in Chapters 4 and 7.

2.3. Restoration after failure.

Most analyses of how to repair damage to energy systems (and, for that matter, of how to prevent, control, and contain that damage in the first place)

have an academic flavor and are often reminiscent of the single-failure criterion occasionally used in nuclear engineering--the assumption that only one thing will go wrong at a time. This convenient but often unrealistic assumption is commonly made when the effects of multiple failures are either too disastrous to guard against (like pressure-vessel rupture) or too complex to analyze; but reactors unfortunately do not read safety reports. The history of major power-grid failures, like the Con Ed 1977 blackout, suggests that, as in real reactor accidents, a complex sequence of unforeseen and interactive technical and human failures is not only possible but likely. Recovery measures designed to handle simple, singular failures will not work when many things have gone wrong and more dominoes are falling every minute. Worse, collapses that were caused deliberately can be expected to exploit, rather than to impinge randomly upon, those secondary vulnerabilities that can inhibit response and recovery. Some lessons from the Con Ed blackout point up the kinds of precautions that can make it possible first to survive, and then to recover from, cascading failures.

Secondary consequences of energy supply failures can often be greatly mitigated by even modest advance warning. In the July 1977 New York blackout, for example, "Most of the nearly 200 subway trains then on the tracks managed to crawl to the nearest stations, thanks to a warning from a quick-witted dispatcher; still, seven trains carrying [fewer than] 1,000 passengers were stuck between stations for [several] hours--and the entire system folded thereafter for the duration." [Newsweek 1977:20] Deterioration of power supplies and drivers' reports of dark or flashing signals enabled dispatchers to order trains into stations via a two-way radio system spanning the 230 miles of tunnels. This "decisive action" avoided major strandings; all passengers were evacuated within 3-1/2 hours with no reported injuries [Federal Energy Regulatory Commission 1978:55]. In contrast, hundreds of rush-hour commuters were stuck between stations without warning when a saboteur switched off power to the central Stockholm subway [Evening Standard 1979].

An intriguing and little-known feature of the New York blackout is that part of a 25-Hz grid (run chiefly for railways) and most of a direct-current grid, both within the city, were able to continue normal operation while the 60-Hz grid crashed, since they were not dependent on it for synchronization and were easily isolated. Unfortunately, they served such relatively small areas that they were not able to provide a bootstrap for 60-Hz recovery operations. Local 60-Hz standby generators generally worked well, maintaining operations at bridges and tunnels (mainly supplied from New Jersey anyhow), hospitals, fire and police stations, and airports. (Flights were suspended overnight, however,

and 32 aircraft diverted, because obstruction lights on New York skyscrapers were out.) Surface transit worked, though some fuel had to be imported from New Jersey for buses. Subway officials controlled flooding by dispatching emergency pumps and compressors [Federal Energy Regulatory Commission 1978:55]. Though most hospital emergency generators worked, four hospitals needed police emergency generators, and thirteen other establishments, mainly medical, needed emergency generators repaired. Con Ed dispatched 18 of its 50 portable generators throughout the city to run lifesaving equipment. Had the hospitals used their own generating plants routinely, as is common in Europe, rather than only in emergencies, they would have achieved higher reliability and obtained their heating and hot water as a virtually free byproduct (Chapter 5).

With basic emergency services (if not domestic tranquility) maintained, what options were open to Con Ed officials facing a darkened city? The rerouting capacity of electricity and gas grids is substantial (pp.87,92ff), provided that key switching points are operable. Reestablishing local supplies, however, may presuppose the availability of scarce resources, both physical and human. In general, utilities have much experience of coping with localized failures, but little if any of improvising in the face of large-scale failures that limit help from adjacent areas--the position Con Ed was in with its grid completely isolated. The restoration procedures of the Northeast Power Coordinating Council at the time of the 1977 New York blackout read simply: "1. Restore frequency to 60 hertz. 2. Establish communication with system operators of adjacent systems. 3. Synchronize with adjacent systems. 4. Coordinate restoration of any load previously shed." [Joint Committee on Defense Production 1977a:105] It is hard to escape the impression that if adjacent areas are also down, or if damage to equipment has been widespread, most utilities' ability to cope would be quickly overwhelmed. Con Ed's were certainly stretched to the limit. To appreciate why, it is worth reviewing how grid restoration works.

The Federal Energy Regulatory Commission [1978:21] describes electric grid restoration as "a complicated, demanding process. Even if all system elements are ready for service, there are three basic problems to be solved: First, the system...must be synchronized with neighboring systems through interconnections; second, substantial time must be allowed for the large steam-turbine generators to be brought up to full output; and third, as generator output becomes available, it must be matched by gradually increasing the connected customer load [which is often beyond the utility's direct control save by switching large areas], so that an approximate balance of generation and load is maintained. Solution of these problems usually involves "sectionalizing" the system [which may complicate reactive balancing and voltage-control problems, as in the Con Ed case]."

To make matters worse, "there are urgent time constraints due not only to the need for restoring service to critical loads but also due to the fact that the condition of some unenergized system components will degrade with time, making restoration even more difficult. For instance, pressurized circuit breakers with electric heaters may fail due to gas liquefaction or loss of air pressure; this will occur more rapidly in cold weather, and they may not become operable again until hours after the restoration of auxiliary service. Also, the capacity of stand-by batteries for operation of critical facilities will be limited. Another time constraint...is the time required to carry out the many hundreds of switching operations necessary to excise failed equipment and lost loads and to secure whatever portions of the system...remain operable." [Econ. Regulatory Adminis.1981:6-9f] Picking up lost loads in the wrong order, or in excessively large blocks, may further damage equipment. Worst of all, some power stations have no "black-start" capability--they cannot restart in isolation, but only if supplied with outside power for auxiliaries or synchronization or both. Some stations which are supposed to have this capability occasionally turn out not to. Clearly, the improvisations that restoration of a crashed grid may require are of such complexity that only people of exceptional ability can be expected to do them smoothly without considerable practice; yet opportunities for that practice are almost nil, and simulation exercises for more than routine local outages are very rare. Utilities are also reluctant to join neighboring utilities in preparedness drills (or in installation of costly reliability interties) because they would have to pay the cost of a benefit shared by others.

Recovery is often limited by the availability of spare parts. The severe fiscal constraints on most electric utilities limit their stocks to routine essentials; only after the 1977 blackout, for example, did Con Ed decide to procure a spare for a phase-regulating transformer whose unavailability had contributed greatly to the blackout, which had previously caused four lesser outages, and which had over a year's manufacturing lead time (supra). It used to be customary for utilities to keep spare sets of large generator coils, large bearings, etc., but with higher unit costs (owing to larger unit sizes) and greater manufacturing specialization, and with the added burden of ad valorem inventory taxes, spares have greatly dwindled [Defense Electric Power Administration 1962:28]. Only the smaller, cheaper, more frequently needed items are now commonly stocked [Joint Committee on Defense Production 1977a: 108]. Spares may also be lost in a major accident through storage in vulnerable locations [id.]* For example, when Typhoon Karen struck Guam in November 1962 with sustained winds of 170 mph and gusts up to 207 mph (equivalent to

*Spare pumps for the Trans-Alaska Pipeline (p.77) are proposed to be stored at the pumping stations themselves--conveniently for operators and saboteurs.

about 5 psi peak overpressure), and electrical distribution systems were badly disrupted, repair was "materially lengthened" by the total loss of vital spare parts stored in light sheet-metal buildings [Chenoweth *et al.* 1963:8]. Similarly, Stephens [1973:16] notes that a five-mile stretch in the Harvey Canal near New Orleans contains an astonishing concentration of oil-well service companies whose services, vital to an entire industry, could become unavailable if bottled up by a simple lock or drawbridge failure.

Few companies have retained the on-site manufacturing capabilities they had when they did much of their own machine-shop work. Though many companies do have portable substations of modest size, and some have spare-part sharing arrangements with adjacent utilities, most major items still have to be imported from relatively remote manufacturers, who may have shortages or production problems of their own. The complexity of modern energy equipment is tending to increase resupply problems and lead times. Stephens [1970:49,53], for example, sampled in 1969 the availability from stock of 3-phase explosion-proof electric motors, and found the total stock of four main U.S. manufacturers to be only 22 motors of 150 hp and up, with smaller sizes faring little better. Most larger sizes required special ordering with delivery dates of months. Just replacing the explosion-proof motors required for a single small crude-oil distillation plant "could use up the nation's entire supply of [such] motors"--and some key components, such as transformers, seem "even scarcer." Such mundane items as the hoses and couplings needed to unload oil tankers are often special-order [Stephens 1973:58]. Even with foresight, there are limits to the insurance that spare-parts inventories can buy: "One pipeline company keeps two of each important piece...of critical equipment on hand, but if three items of the same [type] were damaged, as much as 19 months delay could be created...." [id:142].

In the best of circumstances, and based on data from 1967 when many components were smaller and simpler than today's, estimated repair times for seriously damaged major components of power systems [Lambert 1976:56-60]--and similarly for other major energy facilities--are daunting. Typically hundreds, and in some cases thousands, of person-days are required to repair substantial damage (an estimated 23,000 for a seriously damaged boiler). Most major repairs require not only small tools and welders but also heavy cranes and hoists. Transporting heavy items such as generator rotors and transformers is an exacting task when transport systems are working normally. In the event of widespread disruption, it could prove impossible. Such items as large transformers, for which spares are often too costly to keep, must nowadays be returned to the manufacturer for many repairs. "Interchangeability of major equipment is generally not possible due to severe matching problems. Thus,

repair or replacement of such components will pose a major post-[nuclear]-attack problem." [id.:60]

Another estimate [Chenoweth *et al.* 1963:38-41] suggests that a minimum of several weeks would be needed to restore a modestly damaged power station to operation under ideal conditions (absolute availability of expertise, labor, money, parts, etc., no radiation or other interfering conditions, no conflicting priorities). The history of even minor repairs in high-radiation-field areas of nuclear plants--some welds have required hundreds of welders over a period of months, each exposed to the quarterly limit--suggest that it would not take much contamination, whether radiological or chemical, to complicate repairs enormously and even to exhaust available pools of skilled workers. For some types of repairs to damaged energy systems, e.g. for replacing large tubular steel in oil and gas systems, manufacturing capacity is already strained to keep up with routine demand, let alone the exigencies of large-scale emergency repairs. (Pipe over about 12" is normally special-order, as are the large motors and other special components associated with it [Stephens 1973:20,34, 96].) If Mideast oil systems suffered major pipe damage, digging up existing U.S. pipelines, cutting them into sections, flying them to the stricken area, and rewelding them might be faster than manufacturing new pipe. Needs for equipment and trained personnel, too, would dwarf any standby capability--as was arguably the case when, during the Three Mile Island accident, industry experts from around the world converged on Middletown. Stephens [id.:iv] notes that automation has so reduced the number of field employees in the oil and gas industry "that the system could not suddenly revert to hand operation", and that since most company repair crews have been disbanded in favor of specialized contractor crews, "Should a number of areas be damaged at once, they could not be repaired in any suitable time to serve an emergency." Recovery from limited damage is hard enough; damage to, say, several refineries in the same area would be "a catastrophe"; damage to many throughout the country would be virtually unrepairable [id.:150; Fernald 1965].

If facilities are so damaged that they must be substantially rebuilt or replaced, construction lead times (neglecting any regulatory approval periods) would probably not be much shorter than in routine practice--of the order of 5-6 years for a sizeable coal-steam power plant or 8 years for a nuclear plant. (Subsequent chapters will contrast this nearly irreducible lead time--a function of the scale and complexity of the technologies--with lead times which are orders of magnitude shorter for many dispersed alternatives.) Elaborate plants also require exotic materials and fabrication techniques whose availability assumes that the highly interdependent industrial economy is intact and flourishing. A single nuclear power plant, for example, includes in its replaceable

core components [Energy & Defense Project 1980:7] 109 metric tons (T) of chromium, 2.65 T of gadolinium, at least 55 T of nickel, 24 T of tin, and 1106 T of hafnium-free zirconium. Other major energy facilities show heavy dependence on potentially scarce and frequently imported materials [Goeller 1980:81-84]. They also depend on an industrial infrastructure whose scale, concentration, reliance on advanced materials inputs and electronics and on automation and exotic skills, disincentives to inventories, and energy- and capital-intensity are a recipe for vulnerability [Joint Committee on Defense Production 1977:II:42-44].

In summary: if an energy source fails, its connections with a supply grid may provide help (backup and restarting) or may merely propagate the failure--a dilemma addressed further in Chapter 4.4. If a whole interdependent energy system collapses, the need of component A to have energy from B and vice versa if either is to operate can only enmesh recovery efforts in rapidly spreading chaos. The wider interdependencies of the stricken energy system on materials and equipment drawn from an energy-dependent industrial system may prove even more awkward. Seen in microcosm by a utility engineer trying to bootstrap up the critical path to recovery, inability to get spare parts from a local warehouse is a local, specific obstacle. But from a macro point of view [Dresch & Ellis 1966:11-12], thousands of similar localized discontinuities in a previously seamless web of industrial relationships could collectively signal its unraveling on a national or even a global scale. Only if materials, skills, and equipment are locally available to cope with disruptions can there be confidence of keeping that web coherent and coordinated. Crucial to that availability is information that enables people and organizations on the spot to harness their latent ingenuity. This theme will recur in later chapters as we explore the accessibility of different technologies to potential improvisers.

2.4. The cost of failure.

The dependence of modern industrial societies on continuous, highly reliable supplies of high-grade energy is a relatively recent phenomenon. The Netherlands today uses about as much oil as all Western Europe did in 1950. We are accustomed to suppose that civilization would be impossible with, say, only half as much oil and gas as we use today; yet the OECD countries used only half as much as recently as 1960, when they were at least half as civilized as now. Ironically, much of today's vulnerability arose from efforts to escape an earlier one: much of the impetus behind the U.S. shift to oil and gas was the memory of the 1919 coal strike, and current reliance on highly vulnerable gas pipelines (Chapter 3) was a response to World War II-era vulnerabilities of

coastal oil shipments to U-boats and of railroad coal shipments to labor problems [Congressional Research Service 1977:I:7-9]. The precariousness of international oil trade is well known--thanks to inadequate preparation and panic buying, a 1% reduction in world oil availability arising from the Iranian revolution in early 1979 caused gasoline lines and a 120% price increase in the U.S.--but the cost of failure could be even higher in a post-oil economy if the measures taken to relieve oil dependence are themselves unreliable.

The frequency and duration of major supply failures is fairly well known. For example, over the past decade about 60 significant failures of bulk electrical supply have been reported per year, averaging about 250 MW each, with a 1250-MW or roughly 100,000-customer interruption occurring about once a year. The 1977 New York blackout, because complete restoration took 25 hours, headed the list of severity (the product of MW, customers, and hours) with 388 billion, but the 16 May 1977 Florida blackout of 1.3 million customers (3.2 GW) for 4.5 hours, with an index of 19 billion, was far from negligible, and several other interruptions were nearly as severe, including one in March 1976 that left parts of Wisconsin blacked out for as long as nine days [Economic Regulatory Administration 1981:Ch. 4].

But while there are plentiful statistics on the size, frequency, duration, and location of supply failures, estimating their cost to society is difficult and controversial. This is not surprising. There is no theoretical basis for quantifying the value of delivering a unit of energy [Lovins 1977; Junger 1976]. Quantifying the value of a unit not delivered raises even thornier problems. Not all kilowatt-hours or barrels of oil are created equal: the lack of one may cost a life while the lack of another may lose no benefit at all. The direct costs may be high in, say, agriculture if the failure prevents a harvest or causes the mass suffocation of ventilation-dependent hogs or poultry; yet on another farm or at another time of year the damage may be negligible. Analyses of outage costs commonly assume that failure to serve a 10-kW demand is ten times as important as failure to serve a 1-kW demand [Glassey & Craig 1978: 336], but this may well be untrue in both economic and human terms. Duration, degree of warning, and foreknowledge of likely duration are also important. Although there is a large literature of efforts to quantify electrical outage costs [Economic Regulatory Administration 1981:Ch. 5], the results are highly subjective, fail to capture many important features of heterogeneous demands, and range over nearly two orders of magnitude. Further, where does one draw the boundary for a cost analysis? At lost income, life, health, comfort, crops, industrial production, gross national product (the usual basis for estimates [Aspen Institute 1980:62] that the 1976-77 oil interruptions cost America about \$20 billion)? At consequential looting [Newsweek 1977]? How can

one handle downstream economic consequences? In the 1977 coal strike, for example, Congressman Brown of Ohio suggested to the Secretary of Labor [Subcommittee on Energy & Power 1978:3] that "there is imminent danger of having lights go out across the State of Ohio," only to be told, "That is not a national emergency." But Rep. Brown then went on to state that "the entire [U.S.] economy will grind to a halt very quickly without Ohio's glass, rubber, steel, and thousands of other component[s]...." If he were right, where would one draw the line in calculating the costs of the coal strike?

The 13-14 July 1977 New York blackout again offers a useful window into the social complexity of energy supply failures. Early estimates of direct costs--made up 39% of riot damage, 24% of national economic costs, and the rest of various social and economic costs--totalled some \$310 million [Congressional Research Service 1978a], or 7% of a national average GNP-day. Con Ed's Chairman thought that figure too low [Subcommittee on Energy & Power 1978a:142]. He was probably right. A more realistic estimate might be of the order of \$1 billion, or about \$100 per person throughout the blacked-out area. The social brittleness that made intolerable "an outage of any period of time in certain areas of our city" [Subcommittee on Energy & Power 1977:69] appeared in uncontrollable riots--although in the 1965 Northeast blackout, the New York crime rate had actually declined [Congressional Research Service 1978a:3], and the Chairman of the Federal Energy Regulatory Commission stated [Subcommittee on Energy & Power 1978a:16] that "In the more than 200 major bulk power interruptions which have occurred throughout the country over the past seven years, the 1977 New York blackout was the only one recording a significant degree of social losses."

On one level, the damage was tidied up: the City administration "sees actual benefits in that the [1977] blackout led to forming stronger merchants' associations and anti-crime programs" [Newsweek 1978:18], and after more than 3000 arrests, over a thousand looters were eventually convicted and sentenced [id.]. But class-action suits charging gross negligence--one totalling \$10 billion [Subcommittee on Energy & Power 1978a:11]--continued to haunt Con Ed. A Small Claims Court judge ruled that the utility "must reimburse...complainants [mostly for food spoilage] unless the company can prove it was not guilty of negligence" [Newsweek 1978:18]. The suits, including one by the City to recover its expenses from Con Ed, proceeded to trial [Podgers 1980], with "severe implications" for the utility industry if the plaintiffs succeeded, in effect, in "making the utilities insurers of public safety." And the most lasting and severe effects may indeed be the unquantifiable loss of confidence in the City's social future [Newsweek 1977] and in the institutions supposed to

protect its residents from such complete breakdown of social order--much as the most lasting effects of the Iranian hostage-taking may turn out to be loss of public confidence in our government's ability to foresee and forestall hostile foreign actions. Such a psychological shock is deep and lasting, and can change what people do far more than can mere economic signals. For example, in Britain, for several years after the 1974 coal strike, more electrical generating capacity was installed privately--in the form of expensive standby generators in homes and factories--than publicly, simply because many people placed a very high premium on not being turned off.

The financial consequences of failure can be catastrophic for particular companies or for whole industries. Recent DC-10 crashes, some of which cast doubt on the maker's design and on the quality of FAA airworthiness procedures, are apparently damaging Douglas's commercial prospects, and seem to have caused heavy financial losses for airlines with major DC-10 investments as some people seek to travel on other aircraft instead. Three Mile Island may be the end of the Babcock & Wilcox nuclear enterprise, may well push General Public Utilities over the brink of insolvency, has reduced the NRC's credibility, and has focused investors' attention on the possibility of catastrophic loss in an industry that was already having trouble attracting funds [Emshwiller 1980]. A single event may seal the fate of an industry that is already financially precarious and has little safety margin left for maneuver. Such far-reaching financial consequences, like the political costs of energy failures, profoundly affect the range and quality of energy options available to our society, and thus affect in turn the resilience of energy supply.

This chapter has considered the generic vulnerabilities of modern energy systems. They are diverse and certainly worrisome. But specific elements of those systems have unique vulnerabilities that are often even worse. We next examine these special, technology-specific problems in Chapter 3, as a basis for abstracting in Chapter 4 some elements of a design science of resilience.

3. DISASTERS WAITING TO HAPPEN: SOME SPECIAL ENERGY VULNERABILITIES

Traditional assessments consider separately the safety of energy systems (whether they are likely to harm their neighbors) and their reliability (whether they are likely to stop working). The previous chapter suggests that for modern energy systems of large scale, cost, complexity, and interdependence, the latter is already a serious problem. But the hazards inherent in some energy facilities are such that loss of their energy supply could be the least of our worries: other side-effects of their failure could be an unparalleled calamity. This chapter will examine several case-studies illustrating this point, and will amplify earlier remarks about the ease with which certain components can be disrupted, whether accidentally or deliberately.

Dependence, both for energy supplies and for public safety, on the integrity of inherently hazardous, easily disrupted energy facilities raises not only technical but social questions. These have received most attention in the context of commitments to nuclear power: Weinberg [1973], for example, saw a need "to examine whether our social visions match our technological inventiveness." His social visions included "a cadre that, from now on, can be counted upon to prevent accident, prevent diversion***in Uganda as well as in the USA, in Ethiopia as well as in England", exercising "great vigilance and the highest levels of quality control, continuously and indefinitely" [Kneese 1973]. Edsall [1974] skeptically noted that "People are forgetful, often they are irresponsible, and quite a few of them suffer from deep-seated irrational tendencies to hostility and violence." These tendencies would have to be rigorously pruned from the population of specialists responsible for the vulnerable energy devices; they "must not make serious mistakes, become inattentive or corrupt, disobey instructions, or the like...: their standard of personal conduct must differ markedly from historical norms for the general population...." [Lovins & Price 1975:16] Hannes Alfvén [1972] puts it more bluntly: "No acts of God can be permitted." Maintaining such exacting standards of personal responsibility and protecting the technical systems from people with lower standards would be difficult in a society that had, for example, overwhelming commercial or political pressures, or social tensions that could give rise to fanaticism or to guerrilla movements or to strikes by key personnel. These broad constraints may imply an unwelcome degree of homogeneity enforced by strict social controls--a concern already reflected in an extensive professional literature [e.g. Royal Commission on Environmental Pollution 1976; Justice 1978; Barton 1975; Ayres 1975; Grove-White & Flood 1976; Sieghart 1979]. Thus the price of some energy technologies may be the very liberties in pursuit of which the United States was founded.

The impact of human fallibility and malice on hazardous, essential, and highly engineered systems is not at root an engineering problem but a people problem. It arises because the world is peopled by human beings rather than by angels and robots. Whether the resulting failures can be kept small enough without an undesirable degree of social engineering--whether the degree of control required to protect fragile technical systems is acceptable in a free society--is a profound political issue beyond the scope of this study. However, differences of opinion on this very question are a prime source of discontent with the introduction of such technologies and hence make them a source of unrest and perhaps a potential victim of disruption.

These problems, too, are not static, but evolve as society evolves. If strong compensatory mechanisms do not turn up, it is at least plausible that "fallibility problems...[will] become more prominent as [vulnerable systems]... proliferate, salesmen outrun engineers, investment conquers caution, routine dulls commitment, boredom replaces novelty, and less skilled technicians take over (especially in countries with little technical infrastructure or tradition." [Lovins & Price 1975:17-18] Already, Alfvén and others have noted a marked decline in the quality of nuclear engineering students in the United States, so a dollar invested in solving outstanding problems will buy less solution in the future than it did in the days of the pioneers.

Even if standards of care can be meticulously maintained, there is no guarantee that the biggest source of risk has thereby been dealt with. Risk assessments normally assume that failures are caused only by random mechanical breakdowns and human errors, but in fact deliberate attempts to cause failures may be far more important. Human intention, which brings technical systems into being, can also disrupt them. Generally a much lower technology is needed to make disorder than order. Whether intention is malicious or reflects mere curiosity and playfulness, its effect is the same. Abrahamson [1974] points out that vastly more aircraft have crashed by intention than by accident. Given "the inherent frailty of a technology that puts hundreds of people in a cylinder of aluminum moving at 600 mph some seven miles up in the air," it is mainly the limited incentive to make a civilian airliner crash, not any security system, that protects them. Unfortunately, as subsequent examples will show, the incentives for violence against certain energy systems are enormously greater than those for violence against airliners. We can appreciate the importance of those incentives only by examining more closely where and how they arise.

3.1. Liquefied natural gas systems.

Long-distance pipelines--for example, from Algeria to Italy--are not a feasible way to export surplus natural gas from major fields to customers overseas. A high-technology way to do this has, however, been developed in the past few decades. The gas is chilled in a costly facility into liquid form at a temperature of -260°F (-162°C), increasing its density by a factor of approximately 620. The colorless, odorless, intensely cold liquefied natural gas (LNG) is then transported at approximately atmospheric pressure in special cryogenic tankers--the costliest nonmilitary seagoing vessels in the world--to a regasification facility, nearly as complex and costly as the liquefaction plant. When needed, LNG can be taken from insulated storage tanks and reconverted to gas. Approximately 60 "peak-shaving" plants in North America also liquefy and store domestic natural gas, simply as a cushion against winter peak demands which could otherwise exceed pipeline capacity. LNG from either source is regasified and distributed to customers by pipeline just like wellhead gas.

One cubic meter of LNG weighs 465 kg (less than half the density of water) and has an energy content of 238 therms (23.8 million BTU) or 25.1 GJ, equivalent to about 4.3 barrels of crude oil. A barrel of LNG thus has about 0.7 the energy content of a barrel of oil. Yet it is potentially far more hazardous [Comptroller General of the U.S. 1978 (hereinafter cited as GAO); Davis 1979; Office of Technology Assessment 1977]. A barrel of burning oil cannot spread very far on land or water, but a barrel (0.159 cubic meters) of LNG, because it is 620 times denser than pure natural gas and because that in turn mixes with surrounding air, can make over 67,000 cubic feet (1910 cubic meters) of highly flammable gas-air mixture. A single modern LNG tanker of 125,000 cubic meters carries the equivalent of 2.7 billion cubic feet of gas or about 20-50 billion cubic feet of flammable air-gas mixture (the flammability limits of natural gas in air are about 5-14%). A 10,000-ton LNG spill on water will probably boil to gas in about 5 minutes [Fay 1980:89]. That gas, moreover, is so cold that it is denser than air, and flows in a cloud or plume along the surface until it reaches an ignition source. Such a plume might extend at least 5 km downwind from a large tanker spill within 10-20 minutes [Williams 1971, 1972]. It might ultimately reach much further--perhaps 10-20 km (6-12 miles) [GAO I:12-15]. If not ignited, the gas is asphyxiating. If ignited, it will burn to completion with a turbulent diffusion flame reminiscent of the 1937 Hindenberg disaster but about a hundred times as big. Such a cloud of flame can be blown through a city, creating "a very large number of ignitions and explosions across a wide area. No present or foreseeable equipment can put out a very large [LNG]... fire." [GAO I:exec. summ. 25]. The energy content of a single 125,000-m³ LNG tanker is equivalent to 0.7 megatons or about 55 Hiroshima bombs.

A further hazard of LNG is that its extreme cold causes most metals to lose ductility, become brittle, and contract violently. If LNG spills onto ordinary metals (that is, those not specially alloyed for such low temperatures), such as the deck plating of a ship, it often causes instant brittle fractures. Thus failure of the special membranes that contain the LNG in tanks or tankers could bring it into contact with ordinary steel--the hull of a ship or the outer tank of a marine vessel--and cause it to unzip like a banana [Thomas & Schwendtner 1972; Dobson 1972], a risk most analyses ignore [Fay 1980:96]. LNG can also seep into earth or into insulation (the cause of the Staten Island terminal fire that killed 40 workers in 1973). Imperfectly insulated underground LNG tanks, like those at Canvey Island in the Thames Estuary below London, can even create an expanding zone of permafrost, requiring the installation of heaters to maintain soil dimensions and loadbearing properties.

The potential hazards of LNG are illustrated by the only major LNG spill so far experienced in the U.S.--in Cleveland on 20 October 1944 [GAO I:exec. summ. 25-27]. A 4200-m³ LNG tank in America's first peak-shaving LNG plant collapsed, and not all the spillage was contained by dikes and drains. Escaping vapors were quickly ignited, causing a second tank to spill another 2100 m³. "The subsequent explosion shot flames more than half a mile into the air. The temperature in some areas reached 3000°F." Secondary fires were started by a rain of LNG-soaked insulation and drops of burning LNG [GAO I:10-8]. By the time the 8-alarm fire was extinguished (impeded by high-voltage lines blocking some streets), 130 people were dead, 225 injured, and over \$7 million (1944 \$) in property destroyed. An area about a half-mile on a side was directly affected, within which 30 acres (12 hectares) were gutted, including 79 houses, 2 factories, and 217 cars. A further 35 houses and 13 factories were partly destroyed [GAO I:10-11]. The National Fire Protection Association Newsletter of November 1944 noted that had the wind been blowing towards the congested part of the area, "an even more devastating conflagration...could have destroyed a very large part of the East Side." It is noteworthy that the plant's proprietors had taken precautions only against moderate rates of LNG spillage, and did not think a large, rapid spillage was possible. "The same assumption is made today in designing dikes" around LNG facilities [GAO I:exec. summ. 27]. The Cleveland plant, like many today, was sited in a built-up area for convenience; the proximity of other industrial plants, houses, storm sewers, etc. was not considered. Less than 6300 m³ spilled, mostly on company property, whereas a modern LNG site may have several tanks of up to 95,000 m³ each. And the cascading series of failures in two inner and two outer tanks was probably common-mode, from a single minor cause [GAO I:12-17].

The future of LNG in the United States is highly uncertain, largely for economic reasons. LNG shipment requires highly capital-intensive facilities at both ends and in between. Their coordination is a logistical feat that exposes companies to major financial risks: "if any of [the system's components is not ready on time]..., the entire integrated system collapses [Aronson & Westermeyer 1981:24]. Like the nuclear fuel cycle, LNG projects require exquisite timing but often do not exhibit it--as when Malaysia was "caught with finished [LNG] carriers before their fields and facilities were ready to begin production" [id.:21]. This uninsurable financial exposure by prospective LNG buyers provides a bargaining chip to sellers, who can simply raise the price and dare the buyers to write off their tankers, terminals, and regasification plants.

This has been happening in 1980-81. Algeria, the major LNG exporter, demanded that LNG be priced at oil parity ($\$6/10^6$ BTU or about $\$40/\text{bbl}$), more than a trebling of earlier prices. The U.S. government found this price--far above the $\$4.47/10^6$ BTU just negotiated with Canada and Mexico--unacceptable. On 1 April 1980, Algeria cut off LNG deliveries to the El Paso Natural Gas Company, idling its costly tankers and terminals at Cove Point, Maryland and Elba Island, Georgia. Though modest imports from Algeria continue at the older (1968-71) Distrigas operation in Everett, Massachusetts, which uses a different pricing structure and Algerian-owned ships, the Cove Point and Elba Island facilities, like the nearly completed Panhandle Eastern Pipe Line Co. terminal at Lake Charles, Louisiana, sit as hostages to price agreement with Algeria. Algeria has somewhat moderated its initial demands, but it and other LNG exporters still intend to move rapidly to oil parity. Partly for this reason, the proposed Point Conception (California) LNG terminal seems unlikely to be built. The economic difficulties of LNG arise in not only the world but also the domestic marketplace: new and probably existing LNG imports cannot compete with domestic gas (let alone with efficiency improvements and some renewable options), and LNG has been saleable only by "rolling in" its high price with very cheap (regulated) domestic gas. Gas deregulation will probably so increase domestic supply and reduce domestic demand as to squeeze LNG out of the market. Acknowledging the bleak economic outlook, El Paso in February 1981 "wrote off most of the equity ($\$365.4$ million) in its six tankers which hauled Algerian LNG to the East Coast." [Aronson & Westermeyer 1981:5]

Despite these uncertainties, some LNG--about 0.1% of national gas use--is now being imported into the U.S., and facilities are available for more. The disturbing vulnerabilities of these facilities will now be surveyed--for tankers, terminals, storage tanks, and trucks--together with analogous vulnerabilities for liquefied petroleum gas (LPG) facilities.

3.1.1. LNG tankers.

Fourteen LNG terminals are operable worldwide. Some are sited in major conurbations, including Boston Harbor and Tokyo Harbor. (Another, built in Staten Island, New York, has remained mothballed.) In 1978 the world fleet contained 38 specially insulated, double-hulled tankers of several designs [GAO], with an average LNG capacity of 46,000 m³. By 1980 this fleet was stabilizing at about 80 tankers [Fay 1980:90], the largest of 165,000 m³-- "enough to cover a football field to a depth of 130 feet" [id.:2-7]. A modern standard LNG tanker of about 125,000 m³ is about 1000 feet (305 m) long, 150 feet (46 m) abeam, and cruises at 20 knots, partly fueled by the 0.13-0.25% of the cargo that boils off each day. LNG tankers carry unique safety equipment and are subject to special rules, usually involving escorts and traffic restrictions, when moving in harbor. Once moored, a tanker discharges its LNG cargo in 10-15 hours at a rate up to 190 m³ per minute (equivalent to about 75 GWT, or the rate at which about 70 giant power stations send out energy). The pipes used in this operation are exposed on the jetty, and lead to at least two tankers'-worth of storage tanks contained (with limitations noted below) by dikes. A typical LNG storage tank, of which most terminals have several, is 140 feet high by 190 feet in diameter (43 x 58 m) and holds 95,000 m³ of LNG with a heat content of 2.4 PJ--equivalent to a quarter of an hour's total energy consumption for the entire United States, or to the energy released in a nuclear explosion of 569 kT (over 40 Hiroshima-equivalents).

LNG tankers have a good safety record, but even the limited reports available show some spills [GAO; Davis 1979]. One LNG carrier has gone aground, and three failed certification owing to cracked insulation [Aronson & Westermeyer 1981]. Double-hulled LNG tankers (unlike single-hulled, pressurized LPG tankers) are relatively resistant to damage by collision or light attack, but could be holed by certain weapons available to international terrorists (or by military-type limpet mines). Onboard sabotage would be relatively straightforward. Manipulation of onboard valves could in some circumstances rupture the LNG tanks from overpressure [GAO I:6-10,-11,-59,-60]. Alternatively, all LNG tanker designs allow internal access below the tanks, and if a tank were deliberately ruptured, ducts open at both ends and running the full length of the cargo area would help to distribute liquid [GAO I:9-21]. Any such substantial spillage of LNG onto the steel hull would probably shatter it. "Only an expert would recognize some types of explosive material as explosives. One LNG ship crew member, trained in the use of explosives, could cause simultaneous tank and hull damage...[which] might initiate an extremely hazardous series of events." LPG ships are even more easily sabotaged [GAO I:9-20].

3.1.2. LNG terminals and storage tanks.

The enormous amounts of LNG and, if it leaks, of flammable vapors make LNG terminals and storage areas highly vulnerable. The world's largest LNG gasification plant, the \$4+-billion facility at Arzew, Algeria, narrowly escaped destruction one night a few years ago when a gas cloud from a leaking tank drifted through it and dispersed without igniting. The Tokyo Harbor terminal has luckily escaped involvement with marine fires and explosions, including at least one major one from an LPG tanker. The Canvey Island terminal downriver from central London recently had its third narrow escape when a 200,000-ton oil tanker collided with a Shell oil jetty at Coryton that protrudes into the river upstream of it [Times 1981]; when the Italian freighter Monte Ulia had sheared off that same jetty, the resulting drift of burning oil and trash barges downriver had narrowly missed the LNG jetty [Davis 1979]. Indeed, one actual and one suspected incident of arson aboard a Texaco tanker had also endangered the Canvey Island LNG terminal [BBC 1981]. Though the Cove Point, Maryland LNG terminal is sited away from population centers, it is 5 miles south--well within plume range--of the Calvert Cliffs nuclear power plant, which probably could not withstand a major firecloud. The Everett Distrigas terminal in Boston Harbor is near Logan Airport, and its ship channel lies under the flight path for at least one runway. A Delta DC-9 on an instrument landing crashed into the seawall short of that runway in 1973. Had a gas tanker been in the channel at the time, it could have been missed by as little as a few feet. A normal flight pattern can bring in planes as low as 100 feet above an LNG ship's masts [GAO I:6-39ff], though the FAA now plans to suspend landings that would do so.

Both the terminals and the far more numerous peak-shaving LNG plants--in 1978 the U.S. had 45 of these ^{each} storing over 23,000 m³, or 3.6 times the total spill in the 1944 Cleveland disaster--are vulnerable to natural disasters or to sabotage. A GAO evaluation of five LNG and LPG sites found that at three, tanks had very small earthquake safety margins; "two of these three sites, including three large tanks, are located next to each other in Boston Harbor." [GAO I:exec. summ. 8] About 5% of all earthquakes have occurred in areas with little known seismic history or active faulting. Boston experienced a major quake of this kind in 1755. (Others at Charleston, South Carolina and New Madrid, Missouri in 1876 and 1811-12 respectively were felt over an area of two million square miles.) The origin of such quakes is unknown [GAO I:3-12f].

Contrary to normal practice in Japan, where LNG tanks are underground, U.S. tanks are above-grade. GAO calculations and experiments suggest that most dikes meant to contain minor leaks from these tanks will in fact fail to

contain at least half of any sudden, major spill, and some thin dikes could fail altogether [GAO I:Ch. 5]. Sudden, massive releases are indeed possible, as in Cleveland in 1944, because "if the inner tank alone fails for any reason, it is almost certain that the outer tank will rupture from the pressure and thermal shock" [id.:exec. summ. 8]. Further, estimates of the critical crack lengths above which a large, fully loaded LNG tank would fail catastrophically range from a conservative maximum of 4.5-8.5 feet (GAO) to 1-1.5 feet (Columbia LNG Corp., for the usual 9% nickel alloy steel cylindrical tanks) [GAO I:Ch. 4]. Actual critical crack lengths could be smaller, but have not been determined by detailed calculation or experiment.

This proneness to brittle fracture implies that relatively small disruptions by sabotage, earthquake, tornado missiles, etc. could well cause immediate, massive failure of an above-grade LNG tank. GAO [I:9-3] notes that the equipment stolen from National Guard armories includes "small arms, automatic weapons, recoilless rifles, anti-tank weapons, mortars, rocket launchers, and demolition charges. A large number of commercially available publications provide detailed instructions on the home manufacture of explosives, incendiaries, bombs, shaped charges, and various other destructive devices. All the required material can be bought at hardware stores, drug stores, and agricultural supply outlets....It is not unusual for international terrorist groups to be armed with the latest military versions of fully automatic firearms, anti-aircraft or anti-tank rockets, and sophisticated explosive devices." But GAO also found that such sophistication would not be necessary to cause a major LNG release. Live firing tests [I:9-12f] "confirmed that the double-wall structure of [LNG]...tanks affords limited protection even against non-military small arms projectiles, and that devices used by terrorists could cause a catastrophic failure of the inner wall." Some tanks allow access to the insulation space through ground-level manholes, or are built in the air on pilings, thus greatly increasing the effectiveness of explosive charges. Single-walled metal tanks, commonly used for LPG, can be readily destroyed by small charges.

In 1978, none of the 16 LNG facilities visited by GAO had an alarm system, many had poor communications and backup power sources, guarding was minimal (often one unarmed watchman), and procedures were lax: "Access to all of the facilities we visited would be easy, even for untrained personnel." [id.:9-11]. GAO sums up the sabotage risk: "Successful sabotage of an LEG [liquefied energy gas, e.g. LNG and LPG] facility in an urban area could cause a catastrophe. We found that security procedures and physical barriers at LEG facilities are generally not adequate to deter even an untrained saboteur. None of the LEG storage tanks we examined are impervious to sabotage, and most are highly

vulnerable." Further, "In many facilities, by manipulating the equipment, it is possible to spill a large amount of fluid outside the diked area through the draw-off lines. LEG storage facilities in cities are often adjacent to sites that store very large quantities of other hazardous substances, including other volatile liquids. Thus, a single cause might simultaneously destroy many tanks, or a spill at one facility might cause further failures at adjacent facilities" [id.:exec. summ. 10f]--including refineries and power stations.

3.1.3. LNG shipments by truck.

More than 75 insulated, double-walled trucks deliver LNG from terminals to over 100 satellite distribution tanks in 31 states [Fay 1980:91], chiefly in urban areas [GAO:exec. summ. 16]. More than 90 truckloads of LNG can leave the Everett Distrigas terminal in a single day [GAO I:7-1]. Though puncture-resistant, the trucks have points of weakness and a very high center of gravity, encouraging rollover accidents [GAO I:7-7]. Each truck carries 40 m³ of LNG, with a heat content equivalent to 0.26 kT or about 1/50 of a Hiroshima yield.

At least twelve LNG truck accidents had occurred in the U.S. by 1978. Two caused spills [GAO I:exec. summ. 16]. One driver blacked out after driving far more than permitted hours and falsifying his logbook [id.:I:7-6]. Luckily, both spills were in rural areas and neither ignited. Most LNG trucks leaving the Everett facility travel on the elevated Southeast Expressway, a hazardous road within a few blocks of the crowded Government Center area. In the first four months of 1977 alone, there were four serious accidents on the Southeast Expressway involving tractor-trailer trucks, one of which fell off onto the streets below [GAO I:7-7f]. An LNG truck would almost certainly break open in such an accident [id.]. The entrances to the Sumner and Callahan Tunnels are about a hundred meters downhill from the Southeast Expressway [id.:7-11]. The area is also laced with basements, sewers, and subway tunnels into which the invisible, odorless vapor would quickly spill. "The 40 cubic meters of LNG in one truck, vaporized and mixed with air into flammable proportions, are enough to fill more than 110 miles of 6-foot sewer line, or 16 miles of a 16-foot diameter subway system"--virtually the entire Boston subway system if the gas actually went that far and if none leaked out [GAO I:exec. summ. 17, I:7-10f]. An LNG spill into a sanitary sewer would vaporize with sufficient pressure to blow back methane through domestic traps into basements [id.:7-11]. Sewer explosions themselves can run for miles [Marshall 1981], even with only a few m³ of flammable liquids [GAO I:9-6], and have been used for sabotage [de Leon et al. 1978:22].

LNG truck drivers are not properly identified nor are their trucks inspected for bombs before loading [GAO I:9-17]. Security is only marginally better than for potato trucks [id.:7-9]. LNG trucks are easily sabotaged. The double walls "are relatively thin,...and can be penetrated by a fairly small improvised shaped charge. Properly placed, such a charge would cause LNG to discharge into the insulation space, causing the outer jacket to fracture and disintegrate." [id.:9-19] The trucks normally operate on a fixed route and are an easy target. Further, a truck could be hijacked for extortion or for malicious use of its cargo. It is "particularly dangerous, because [it allows]... the easy capture, delivery, and release of a large amount of explosive material any place the terrorist chooses." [GAO I:exec. summ. 18]

3.1.4. Analogous hazards of liquefied petroleum gas (LPG).

Liquefied petroleum gas (known in rural areas as "bottled gas") is processed from natural gas or crude oil and consists almost entirely of either propane or butane, delivered directly as a liquid rather than being regasified and piped like LNG. It thus requires many small shipments, yet makes up approximately 3% of all U.S. energy supplies. Although its use is far more widespread, well-known, and long-standing than that of LNG, and although in certain respects it may be even more hazardous, LPG is less well studied and regulated.

Unlike methane (the main constituent of natural gas), propane and butane liquefy at normal temperatures if sufficiently pressurized--at 60°F (15.6°C), to about 110 or 40 pounds per square inch (7.5 or 2.7 bar) respectively [Congressional Research Service 1977:III:406]. Alternatively, they can be liquefied at atmospheric pressure by cooling them to about -44°F and +31°F respectively. About 85% of the LPG in bulk storage is kept under pressure in underground salt domes or caverns [GAO I:exec. summ. 5]; the rest is stored aboveground in tanks, often small ones. In 1978 the U.S. had only 20 aboveground LPG storage facilities holding over 23,000 m³. Most LPG is transported through some 70,000 miles of high-pressure pipelines, and the rest via 16,000 pressurized rail cars (no LNG moves by rail) and 25,000 pressurized tank trucks. A large LPG truck, like its LNG counterpart, holds about 40 m³. Being single-walled and under pressure, LPG trucks are more vulnerable than LNG trucks to breakage through accident or sabotage, and they are also more likely to explode in fires because they are uninsulated and their cargo creates very high pressures by boiling when exposed to heat.

Many LPG truck accidents have occurred worldwide [Davis 1979]. A 34-m³ truck, for example, overturned in 1973 on a mountain road above Lynchburg, Virginia, creating a fireball about 130 m in diameter [GAO I:7-12]. In a

far more destructive accident near Eagle Pass, Texas in 1975, a 38-m³ LPG tank broke loose from its trailer. Two explosions blew the front of the tank about 500 m and the rear (in three pieces) some 240 m. Sixteen people were killed and 35 injured [GAO I:7-13]. In West St. Paul, Minnesota, a midnight LPG delivery fire in 1974 killed four people and demolished large sections of three apartment buildings; the fire department's LPG emergency procedures could not be used because of snow [id.:7-14]. Many LPG accidents have occurred through faulty repairs, delivery procedures, or valve operations [id.:7-13].

LPG railcars, containing about 115 m³ each (0.7 kT equivalent), "are involved in many of the 10,000 railroad accidents that occur in this country each year. There are often more than 10 consecutive LPG cars on a train. Each car can form a 10-second fireball about 120 m in radius [Fay 1980:100]. If vapors from one LPG car ignite, the fire may rupture an unpunctured car in a 'Boiling Liquid Expanding Vapor Explosion,' or BLEVE [where sudden depressurization rapidly boils and expels the LPG as an aerosol-vapor-air mixture]. Each fire and explosion contributes to the heating and weakening of neighboring cars and makes additional explosions more likely. A BLEVE can rocket a 45,000 pound (20 T) steel section of a tank for a quarter of a mile. This is what happened in a derailment near Oneonta, New York, in 1974. LPG vapor from a crushed LPG car quickly ignited and formed a fireball. Fire fighters attempting to cool down several other LPG cars were caught in a subsequent explosion; 54 were injured....In a 1974 railyard accident near Decatur, Illinois, an LPG railcar was punctured; the resulting cloud did not ignite immediately, but spread and then exploded over an area one-half by three-quarters of a mile. [The blast was felt 45 miles away: GAO I:8-3.] There were 7 deaths, 349 injuries, and \$24 million in damage. Litter and debris...covered 20 blocks of the city....LPG railcars travel through densely populated areas of cities, even cities which prohibited LPG storage." [GAO I: exec. summ. 19] Some 100,000 LPG railcars are moved each year in the U.S. [GAO I:8-1]. They are only a tenth as numerous as tankers carrying other hazardous cargoes, and are thus likely to occur in the same trains with chlorine, oil, industrial chemicals, etc. Railway switchyards have had ammunition trains blow up; a few years ago a chemical tank car being shunted in Washington State exploded with a force of several kT. An LPG train could easily be derailed at any desired point; "youth gangs frequently place obstacles on tracks which delay freight trains in New York City just to harass the trainmen." [GAO I:8-14] The 5/8" steel wall of an LPG railcar "can be easily cut with pocket size explosive devices [or by] many other weapons commonly used by terrorists...." [id.:9-18] LPG vapors are heavier than air even at ambient temperatures, are flammable in about the 2-9% range, and can detonate.

LPG terminals, as well as shipments by road and rail, penetrate the most vulnerable parts of our industrial system. GAO [I:2-11], for example, shows an aerial photograph of a major LPG receiving terminal near Los Angeles Harbor. Its propane storage tanks, a stone's throw from the Palos Verdes earthquake fault, are surrounded on one side by a large U.S. Navy fuel depot and by a tank farm, and on the other side by a dense residential area that runs for miles--all within the range of an LPG conflagration. A broadly similar 50,000-m³ refrigerated propane tank in Qatar, designed by Shell International, suddenly collapsed in 1977, sending liquid propane over the dike; the resulting explosion destroyed the LPG facility surrounding the tank. In France, eleven people died and 70 were injured when vapor from a leaking butane tank was ignited by a truck passing 160 m away, leading to the explosion of eight butane and propane tanks [GAO I:21-6f]. In practical effect, the most densely industrialized and populated areas in America have potential bombs in their midst, capable of causing disastrous explosions and firestorms without warning. "Nuclear power plants," as GAO remarks [I:exec. summ. 8], "are built to higher standards than any other type of energy installation, much higher than those for LEG installations. Nevertheless, they are never located in densely populated areas. We believe that new large LEG facilities also should not be located in densely populated areas." Even existing LEG facilities pose a formidable hazard.

LNG shipments and facilities likewise perforate America's industrial heartland. Even the most sensitive "choke points" are put at risk. In February 1977, for example, LNG was trucked along the Staten Island Expressway and across the Verrazano-Narrows and Goethals Bridges [id.:7-8]. Seven Mile Bridge, the only land access to the lower Florida Keys, was heavily damaged by a recent propane-truck explosion [Los Angeles Times 1981c]. It is apparently common for LNG shipments to pass near major oil, gas, and nuclear facilities, few if any of which could withstand envelopment in a burning gas cloud. While many local authorities would like to restrict such shipments before a catastrophe, the regulation of such interstate commerce is federally preempted; and so far, despite the devastating criticisms in the GAO report, the dozen or so responsible Federal agencies have done little of substance to improve safety.

Perhaps additional LNG imports, brought by 80-plus large tankers into a half-dozen U.S. terminals, will never happen as enthusiasts once hoped, if only for the economic reasons alluded to earlier. But unless tackled directly, the clear and present dangers from present LNG and--on a far greater scale--LPG operations will persist. Later chapters will argue that all the energy now supplied by LNG and LPG can be replaced by much cheaper sources which do not compromise preparedness.

3.2. Oil and gas systems.

Oil, gas, and natural gas liquids, which together supplied about 73% of America's total primary energy in 1979, are transported, processed, stored, delivered, and marketed by an extraordinarily complex technical system that must rank among the greatest technical achievements of our species. A veteran observer of that system, however, notes in a classic study [Stephens 1973:62] that "The system is delicately balanced and extremely vulnerable and can be readily interrupted or damaged by natural disasters, by sabotage, or by enemy attack. An attack concentrated on the system, or even on certain segments or fragments of it, could bring industrial activity and transportation to a standstill." A followup study of the natural gas system alone [Stephens 1974:87] identifies an ominous trend: "It is recognized that certain impalpable conditions exist that might be quite subtle in nature, yet have the potential of great impact on the industry if such were damaged. An attempt was made to seek out these conditions but it is certain that many remain unidentified. It is also evident that as the industry becomes more efficient, handling larger volumes of gas and products, as flow lines extend farther seaward linking more deep water platforms, that frailty of the system is increasing. There are critical locations and junction points that concentrate facilities and large gas volumes into centers which are easy targets....Unfortunately, there appears to be a trend away from flexibility of the system....The Icarian nature of expansion of the industry increases vulnerability daily."

The links between the oil and gas industry and other equally vulnerable systems are intricate, pervasive, and increasing. "Our present economy is so finely tuned, because of the need to effect as much efficiency as possible, that an interdependence has been developed between transportation, manufacturing, electric power generation and the petroleum and natural gas industry, [so] that one can hardly exist without the other. Each depends on and each serves the other. A widespread failure of one industry is certain to seriously affect another. The natural gas industry cannot function without pipe, electric motors, pumps, chemicals and a host of other items, nor can many manufacturing industries exist without the products of the gas system or that of the closely related petroleum system." [Stephens 1974:79-80] The natural gas industry also provides the feedstock from which is made "all or most of the rubber, plastics, fertilizer, paint, industrial solvents, medicines and many other items used daily in the United States. A loss of this [feedstock]...would be devastating in time of a national emergency."* [id.:4] The functioning of the

*60% of U.S. petrochemical capacity is on the Texas Gulf Coast [OTA 1979a:69].

oil and gas industries in turn depends on internal linkages: "the links between segments could be the major frailty." [Stephens 1973:136]

3.2.1. Oil and gas fields and shipping facilities.

The vulnerability of the oil and gas system begins (exploration aside) at the wellhead and in the reservoir. At a conservative \$30 per barrel, the oil deposits in the Persian Gulf region are worth over \$270 trillion [Taylor 1980: 307], or over 100 U.S. GNP-years--perhaps the ripest plum in the world. OPEC has lately earned a negative real rate of return on extracted oil: a barrel lifted in January 1974 and sold for \$11 would by 1980 have been worth about \$18 if invested in U.S. Treasury bonds, yet the same barrel left in the ground could by 1980 have been sold for at least \$32 [Foley & Lönnroth 1981:7]. But even though oil appreciates (so far) faster in the ground than in a Swiss bank, the oil itself is in the Gulf, not in Switzerland, and its proprietors understandably worry that they may not be around to enjoy the future revenues.

The cultural, political, and military instability of the Gulf [Deese & Nye 1981] needs no emphasis here. Even friendly, relatively stable exporters of oil to the U.S. cannot be considered entirely reliable: Canada's current Provincial/Federal tug-of-war has already curtailed many Albertan oil and syncrude activities. But present U.S. oil imports are sadly lacking even in the safety of diversity. About a third of the non-Communist world's oil supply comes from the Gulf, and about a third of that in turn comes from the highly congested area at the head of the Gulf (including Kuwait) [Rowen 1980]. Within major oil-exporting countries, moreover, there is astonishing physical concentration. One Saudi oilfield lifts 5 million barrels per day--more than any other country except the U.S. and U.S.S.R. Saudi Arabia lifts about 9.5 Mb/d from a mere 700 wells, whereas the U.S., far further along in its depletion cycle, lifts 10.2 Mb/d (including natural gas liquids) from some 600,000 wells [Taylor 1980:304].

The delivery systems for that concentrated gush of oil are likewise highly localized. Kemp [Deese & Nye 1981:370] notes that "The oil wells themselves are obvious targets[;] so are the collecting systems, which pump oil through pipes from the fields to local terminal facilities. [These]..., containing gas-separation plants, local refineries, storage tanks, and loading facilities, could also be potential targets. And the pipelines and tankers carrying oil to destinations beyond the Gulf are no less vulnerable." It is often forgotten that Libya's leverage to begin the oil price spiral came from the Suez Canal closure and destruction of a pipeline [Deese & Nye 1981:9]. "In early 1978," according to Stobaugh & Yergin [1979:36], "there were reports that Iraq was

training frogmen and desert demolition squads, and that Palestinian terrorists had been found on tankers." There has been at least one intelligence alert [Times 1975a] that terrorists were about to rocket or hijack a supertanker in the Straits of Hormuz--perhaps the most critical of several maritime bottlenecks through which tankers bound to main importing countries must pass. (No more than a few large vessels sunk there could block the Straits for a long time.) Other sensitive shipping paths include the Bab-el-Mandeb Strait (which Egypt blockaded in 1973), Sharm-el-Sheikh, the Cape of Good Hope, and the Straits of Malacca and Singapore. TAP-Line, a 0.5-Mb/d pipeline opened in 1950 from Saudi fields to the Zahrani terminal near Sidon, in southern Lebanon (currently a turbulent area), was repeatedly attacked by saboteurs and during the Arab-Israeli wars (it passes through the Golan area of Syria), and was eventually so damaged by bombings that it was shut down altogether [SIPRI 1974:55; Congressional Research Service 1977:III:169]. Even before the 1980 outbreak of hostilities between Iran and Iraq, Iranian oil facilities had suffered severe damage from sabotage: a combination of poor labor relations, repression of the Arab minority in Khuzistan, and provocation of Iraq had led to frequent bombings of pipelines and pumping stations [Deese & Nye 1981:66], including the destruction of at least 14 pipelines within three days [New York Times 1980].

Offshore oil facilities, proposed as a replacement for OPEC oil imports, are nearly as vulnerable--sitting ducks laden with highly flammable fuels under pressure [Kessler 1976; Kupperman & Trent 1979:72]. Scottish Nationalists have already bombed an onshore North Sea pipeline. The British government's five-ship, four-plane task force to patrol offshore North Sea installations [Donne 1975] is likely to be ineffectual. Though each platform has a "safety zone" of 500 m, illegal trawlers have sailed within 30 m [Faux 1981] because the fishing is richer there, and there is nothing to stop a vessel from actually attacking a platform. The oil rigs may be vulnerable to mere collisions: a rig in the Norwegian sector capsized in 1980, killing 123 people, because it could not cope with the collapse of one of its five supports, which had been weakened by an improperly cut hole [Washington Post 1981a]. One \$50+-million platform may carry over 40 wells [Stephens 1979:208], and junctions of gathering lines frequently bring 50-100,000 b/d or more into a single, "totally unprotected" line, often in shallow water or swampy areas where heavy equipment, whether floating or onshore, cannot operate [Stephens 1973:34]. More than three simultaneous platform fires "would completely overwhelm available control and remedial facilities of the Gulf Coast"--which could all be bottled up by sinking a small barge [Stephens 1974:93]. In current practice, platforms in and along the Gulf of Mexico must be shut in and deserted (as offshore platforms off New England

would presumably have to be) during severe storms. This interrupts the filling of natural gas storage, "depended upon more each year for peak load cushions," and might lead to widespread shortages if a late hurricane in the Gulf coincided with an early cold spell in gas-heated areas [Congressional Research Service 1977:III:193]. Three North Sea gas platforms and a drill rig have been temporarily shut down by a mere hoax telephone threat [Guardian 1975b].

The vulnerability of oil imports can also interact with that of the domestic oil systems which would have to substitute for interdicted imports. If, for example, crude oil imports to East Coast refineries were shut off, virtually the only fluid fuel supplies to the Northeast would come through one refined products pipeline (Colonial) and a few natural gas pipelines--all of which could be disabled by a handful of people. The 48-inch Trans-Alaska Pipeline System (TAPS), currently supplying 1.2 million b/d (10.5% of U.S. refinery runs) and displacing oil imports worth nearly \$500 per second, is an equally tempting leverage point. It runs aboveground through remote country for 800 miles, and there is no other way to deliver its North Slope oil. Though its proprietors annually spend about a thousandth of the line's replacement cost on obvious security precautions, it is impossible to prevent determined sabotage.

Major parts of TAPS are invisible and inaccessible to repair crews by air or ground for up to weeks at time in the winter. "If this almost uniquely vulnerable...system were interrupted for three weeks [in winter], the heated oil [nine million barrels of it] would cool to the point that it could not be moved, putting the pipeline out of service for six months." TAPS was bombed in 1977 without penetrating the pipe wall, but a second bombing in February 1978 spilled about 15,000 barrels and shut down the line for 21 hours [Comptroller General of the U.S. (hereinafter cited as GAO) 1979:30]. (Alyeska's security manager still "does not perceive a sabotage threat in Alaska." [id.]) The vulnerability of the eight pumping stations, remotely controlled from Valdez, was illustrated in July 1977 when operator error blew up a station in a relatively flat area. After 10 days, the station was bypassed and pumping resumed, at half the usual rate; but had the failed station been one of those required for pumping over the mountains, pipeline capacity "would have been reduced substantially more, or even curtailed altogether." [GAO:39] "Despite an intense rebuilding effort, it took about 9 months to rebuild the pump station." [id.] In a less favorable location or season, it would have taken longer. A Senate Subcommittee [Senate Judiciary Committee 1977] "was stunned at the lack of planning and thought given to the security of the pipeline before it was built" [Congressional Research Service 1977:III:169] and recommended that DOE set up an Office of Energy Security. The Bill died and was not reintroduced.

Oil imported to the contiguous United States other than from Alaska or Canada arrives by tanker: some directly in the small and medium-sized tankers that can enter conventional ports, and the rest, directly or indirectly, in vast, lumbering Very Large Crude Carriers. That these vessels are vulnerable to disruption needs no emphasis, as they manage now and then to do themselves in without assistance [Mostert 1974].

3.2.2. Oil storage and refineries; gas processing plants.

The average barrel of oil takes about three months to get from the well-head to a final U.S. user [Marshall 1980]. Along the way are oil inventories "in the pipeline"--aboard tankers, in various tanks, and of course in pipelines themselves. According to Petroleum Intelligence Weekly [Federation of American Scientists 1980:6], however, about 3.3 billion barrels of oil worldwide, or nearly two months' world oil use, represent an "absolute minimum unusable quantity" needed to fill pipelines and otherwise keep distribution systems flowing. A further 0.5 and 0.8 billion barrels are respectively held in stockpiles requiring a political decision for their release and in ships en route to their destinations. Thus only stocks in excess of about 4.6 billion barrels worldwide "can be considered commercially usable inventory." In late 1980 the inventory was around 5.7 billion barrels, about 0.4 billion above normal--four times the amount then held in the U.S. Strategic Petroleum Reserve. These stocks provide a degree of elasticity to the tightly coupled world oil system.

Oil stockpiles, however, are vulnerable: indeed, the Strategic Petroleum Reserve appears to be the only Federal energy project in the U.S. which has from the start been careful to minimize its vulnerability through appropriate security measures, analyses, siting, stocking of spare parts, etc. (The below-ground storage caverns are of course relatively well protected; only the surface installations are of much concern.) That these precautions were not idle was borne out in Rhodesia in mid-December 1978 when Black nationalists using rockets and tracer bullets burned out a 40-acre oil storage depot outside Salisbury, destroying half the complex and nearly half a million barrels of products which the embargoed Smith regime had painstakingly accumulated from Iran and from synthetic-oil plants in South Africa. The monetary cost alone, about \$20 million, increased the projected national budget deficit by 18% [New York Times 1978b,c]. A 1972 Palestinian/Red Brigades attack crippled the Trieste refinery, burning out four huge storage tanks [Bass et al. 1980:44; Sterling 1978:41]. Even the U.S. is not immune: a St. Paul, Minnesota oil tank farm was bombed on 4 November 1970 [Burnham 1975:122].

Oil refineries are typically the most vulnerable, capital-intensive, and indispensable element of the oil system downstream of the wellhead. Since most devices are equipped to burn specific refined products, not crude oil itself, it is not possible to substitute other modes for refining as it is for oil delivery. Just as three-fourths of domestic oil is lifted in only four states [Stephens 1979:208], so more than 69% of refinery capacity is clustered in six states, and over half in only three states (Texas, California, Louisiana) [*id.*: 208]. Of nearly 300 major refineries, 22 sites have 1-3.6% of national capacity each. Many of these depend on common pipelines, ports, and repair facilities. Essentially all the sites are subject to hazards ranging from earthquake to nuclear or LNG accident to military attack. Local concentrations are remarkably heavy: for example [Stephens 1973:148-149,52], East Baton Rouge Parish, Louisiana, contains the then largest U.S. oil refinery (Exxon, 0.5 million bbl/d --Baytown, Texas is now 0.6), many petrochemical plants, Kaiser Aluminum, docks, river terminals, and two major river bridges. Through the same area run the Plantation and Colonial pipelines, carrying most of the East Coast's and much of the South's refined products. A nuclear bomb on New Orleans could simultaneously kill most of its inhabitants (including many with unique technical skills), flood the city, destroy control centers for offshore oil and gas operations, destroy many petroleum company headquarters, stop traffic both across and on the Mississippi River (isolating petroleum workers from their homes or plants, depending on the time of day), damage a shipyard and refineries, and destroy port facilities. The Office of Technology Assessment, working with the Defense Civil Preparedness Agency, found [OTA 1979a:64] that destruction of the 77 largest U.S. oil refineries would eliminate two-thirds of U.S. refining capacity and "shatter the American economy"--as well as destroying, in the assumed 80-warhead nuclear attack, 3-5 million lives and many ports, petrochemical plants, and other heavy industrial facilities.

It does not take a one-megaton warhead, however, to destroy a refinery: a handful of explosives, or sometimes just a wrench or the turning of a valve, will do as well. Refineries are congested with hot, pressurized, highly flammable, and often explosive hydrocarbons. "There are over two hundred sources of fire in an average refinery, so uncontained gases have little trouble finding an ignition source." [Stephens 1973:52] Heavy pressure vessels may themselves explode if shocked [*id.*]. "Loosened flange bolts in a hydrogen line, moving a gas that burns with a colorless flame and which even in a small mass, auto-detonates at relatively low temperature, could...completely destroy vital segments of a refining process. A broken valve bonnet in an iso-butane line or an overflowing hot oil tank has been known to cause millions of dollars damage."

[id.:101] Some parts of the refinery are essential to its working at all; so if a crucial third of the plant is destroyed, output may be reduced to zero, not merely by a third [id.:141]. Refineries involve such complex plumbing and equipment, often custom-made, that repairs are slow and difficult: reconstruction of substantial equipment can take months [Stephens 1970:105] or years.

Stephens [id.:vii] lists recent trends which have tended to make refineries more vulnerable. His concerns include: the push to enlarge plants within the same boundaries, so increasing congestion; localization of capacity, especially in areas "having frequent hurricanes, tornadoes, floods and earthquakes, and by or near tide water"; making more light products, which require the use of highly explosive hydrogen and make process control more critical and equipment "more sensitive to possible detonations"; widespread dependence on purchased electricity, even for vital functions; reliance on centralized, hard-to-repair computers; reduction of the work force, leaving fewer skilled people (or people of any description) on site to cope with emergencies; reduced spare-parts inventories; relatively flimsy construction, especially in control and switchgear houses, cooling equipment, and exposed piping and cables; larger storage tanks and supertankers; and bigger terminals with higher unloading rates, "resulting in a concentration of highly combustible products and crude supply into a relatively small area." A more volatile set of trends is hard to imagine. Nor is refinery sabotage a mere fantasy: on 26 January 1970, the "United Socialist Revolutionary Front" caused "millions of dollars" in damage to four units of the Humble refinery in Linden, New Jersey [New York Times 1970]. The national disruption from refinery outages could be maximized by careful selection of the targets, since U.S. refinery flexibility is unusually low [Deese & Nye 1981:40]. Flexibility could be improved through overcapacity, as is currently the case--in spring 1981, refinery utilization was at an all-time low of about 68% [Martin 1981]--but the cost of that inadvertent redundancy is far higher than the industry would ever incur intentionally.

Natural gas processing plants, analogous to (though simpler than) oil refineries, are a similar point of weakness, and have in fact also been sabotaged: the Black September group blew up two such plants in Rotterdam on 6 February 1971 [Energy & Defense Project 1980:15]*. Unlike crude-oil refining, gas processing is not an absolutely vital step in the short term, and can be temporarily bypassed [Stephens 1974:27]. But this cannot be long continued, for three reasons. First, dissolved natural gas liquids can cause transmission problems, and if not extracted, can remain in gas delivered to final users; "the sudden onrush of 'gasoline' out of gas burners could be very dangerous."

*Fifty heavily armed rightists also took over and threatened to blow up a remote Bolivian gas processing plant of Occidental Petroleum Co. in May 1981, but left for Paraguay after several days' negotiations [Los Angeles Times 1981i].

[id.:15] Second, unextracted water could "freeze and cause considerable damage at low spots in the line" [id.], and makes traces of hydrogen sulfide or carbon dioxide highly corrosive to pipelines [id.:24]. Third, unprocessed gas is more hazardous: it often contains highly toxic hydrogen sulfide, and the presence of even small amounts of low-flashpoint higher hydrocarbons will vastly extend the flammable and explosive limits of gas-air mixtures. Some common impurities are so flammable that the mixture can be ignited by a "static spark or one made by imbedded sand in a person's shoe sole striking the rungs of a steel ladder" [id.:87,90]. Gas processing, then, cannot be omitted for long without grave occupational and public risks. Yet gas processing plants are at least as vulnerable as refineries, take a year and a half to rebuild "assuming normal delivery of equipment and materials" [id.:27], and are often centralized. A single plant in Louisiana, the world's largest, provides 1.85 billion cubic feet per day to the East Coast--the equivalent of over 20 huge power stations' output [Stephens 1973:149]), or about 3.4% of America's total natural gas use (which is in turn a fourth of total energy use). An alarming 84% of all interstate gas is from Louisiana (53%) or flows from Texas mostly via Louisiana (31%): Louisiana is to U.S. gas as OPEC is to world oil [Stephens 1979].

3.2.3. Pipelines and alternatives.

Oil pipelines move about three-fourths of the crude oil used by U.S. refineries and about one-third of the refined products moved from refineries to consumers. These pipelines "are highly vulnerable to disruptions caused by human error, sabotage, or nature. Damage to key facilities on just a few pipeline systems could greatly reduce domestic shipments, causing an energy shortage exceeding that of the 1973 Arab oil embargo" [GAO 1979:i]. The flow of petroleum through just the Trans-Alaska, Colonial, and Capline pipeline systems is equivalent to about three-fourths of total U.S. petroleum imports, or over 1.5 times the maximum U.S. import shortfall during the 1973 oil embargo, or about 8 times U.S. imports from Iran when those were stopped in 1978 [id.:34].

"Pipelines," remarks John Jimison [Congressional Research Service 1977: III:159-160], "carry huge quantities of energy...in continuous operations stretching over thousands of miles....[They] were constructed and are operated with almost no regard to their vulnerability to persons who might...desire to interfere with this vital movement of fuel. They are exposed and all but unguarded at innumerable points, and easily accessible even where not exposed over virtually their entire routes....[T]his vulnerability of the most important energy transportation systems of the Nation threatens the national security."

Jimison continues: "Although all forms of energy movement are vulnerable to some extent, pipelines are perhaps uniquely vulnerable. No other energy transportation mode moves so much energy, over such great distances, in a continuous stream whose continuity is so critical an aspect of its importance." While continuity is even more important in electric transmission, Jimison is certainly right about both the density and distance of energy flow in pipelines--both the 123,000 miles (in 1975) of crude oil and refined product transmission lines and the 187,233 miles (in 1975) of principal gas pipelines. The liquid- and gas-carrying pipelines have both shared and unique vulnerabilities; those not mentioned in the previous chapter will now be surveyed.

As Jimison says [*id.*:166-167], "Little can be done to stop a determined, well-equipped, and knowledgeable saboteur or terrorist" from disrupting a pipeline, since "It would not be feasible to monitor the entire length of a pipeline frequently enough to prevent any action," and virtually "no...security precautions were taken in that safer day when most...pipelines were built." It is nonetheless important to understand both the potential contributions and the inherent limitations of such security measures as can be taken.

Gas and oil pipelines, ranging up to 48" (122 cm) in diameter, and frequently laid in parallel groups on the same right-of-way, are welded from steel using special specifications and procedures. They are ordinarily buried in a 6-foot trench, enough to protect them from bad weather but not from earthquake or ground shock: major pipelines in such seismic areas as St. Louis, Lima (Ohio), Socorro, and Salt Lake City appear to be at risk [*id.*:195]. The main cause of damage to buried pipelines has so far been accidental excavation, implying that deliberate excavation is also possible. (It could be done instantaneously with military-type shaped-charge excavating devices.) Mainly to prevent accidental damage, buried pipelines are clearly marked, especially at road and waterway crossings, as required by law. Extremely detailed maps periodically published by Federal agencies and by the petroleum industry--some scaled at 1.5 million to 1 or less--enable anyone to locate pipelines and allied facilities without difficulty.

Merely penetrating a pipeline may interrupt its flow and cause a fire or explosion, but unless it allows air into a gas line in explosive proportions, the damage will be local and probably repairable in a few days or (if the industry had to cope with several substantial breaks simultaneously) weeks. Pipelines can be penetrated or severed using low technology--for example with thermite or improvised shaped charges. Commercially available shaped charges are used in the oil and gas industry itself for perforating pipe, and have apparently been used against pipelines or tanks by saboteurs [Stephens 1973:142].

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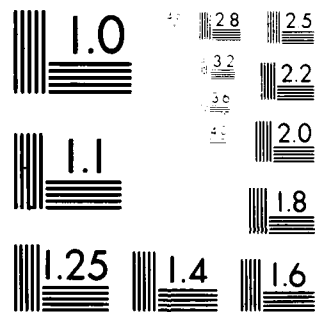
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MICROCOPY RESOLUTION TEST CHART
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Even if a pipeline were somehow completely destroyed, it could be relaid at a substantial rate: "under the most favorable circumstances, small-diameter lines of 6 to 8 inches can be constructed as rapidly as 3 miles or more per day, and large-diameter lines of 30 to 36 inches at one mile or more per day. Under extremely adverse conditions the [respective] rates...are 3,000 to 4,000 feet per day [and]...1,000 to 1,500 feet per day." [Goen et al. 1970:69-70] (Rates in swampy areas are often much lower.) But far more vulnerable and less repairable than pipelines themselves are their prime movers--pumping stations for oil, compressor stations for gas--and such allied facilities as interconnections, metering and control stations, and input terminals. River crossings, either on a bridge or under the riverbed, are similarly vulnerable and complicate repair; further, dropping the bridge can at the same time stop navigation (including tankers and barges associated with an oil terminal or refinery), block traffic, and hinder the delivery of repair equipment [Stephens 1973:46, 96,101]. Significant damage at any of these points can reduce or stop fuel flows for a half-year or more [GAO 1979:15; Stephens 1974:v,91].

As the earlier TAPS example illustrates, the impact of damage to a pumping station depends on the terrain. Depending on the lift required, the distance between oil pumping stations can vary from a few miles in mountainous country to nearly 200 miles on the flats [Goen et al. 1970:60]. Because the engines and pumps are very large (thousands of horsepower) and not a stock item, and because some "may be specifically designed for a particular system," replacement can take from a half-year to a year [GAO 1979:22,24]. Meanwhile, pipeline flow may be reduced by a third or more or even halted. Damage to successive stations in line, or to one preceding a high lift, would be most harmful.

Stephens notes [1973:34] that "Pipelines are easy to sabotage. A double premium accrues to the saboteur's account--the loss of oil and an extensive fire that might ensue. A trained group of a few hundred persons knowledgeable as to the location of our major pipelines and control stations and with destruction in mind could starve our refineries from crude." Likewise, Goen et al. [1970:62-64], in a nuclear targeting exercise, calculated that the destruction of 8 terminals, 68 pump stations, 27 combined terminal/pump stations, and 23 adjacent pipelines would disable all 1968-69 U.S. refined-product distribution pipelines down to and including 6", isolating the refining areas from agricultural and industrial areas. But in fact, immense mischief could be done by only a few people if they picked the right targets from the copious literature available. Goen et al. start in this direction in noting that only six hits could disrupt pipeline service between the main extraction areas and the East and Midwest. But in fact the concentration is even greater than that

might indicate. GAO [1979] focuses on only three pipelines: TAPS, already described, Colonial (mentioned in Chapter 2.1.7), and Tapline. These three together contain less than 3% of American oil pipeline mileage, yet carry about 18% of national crude oil consumption and 12% of refined product consumption.

The Colonial system dominates the U.S. refined-products pipeline market, carrying about half of its total barrel-miles [Goen *et al.* 1970:62] in 4600 miles of pipe over a 1600-mile span. Its products supply more than half the refined-product demand in seven states (VA, NJ, NC, MD, TN, SC, GA), 15-50% in five more (AL, DC, MI, NY, PA) [GAO 1979:15]. "Other pipelines or transportation modes cannot absorb enough" to replace this flow [*id.*:iii]. Tapline, a 40-inch, 632-mile, 16-pump-station crude oil pipeline shipping 1.2 Mb/d from St. James, Louisiana to Patoka, Illinois, provides a quarter of the input to Midwestern refineries, is likewise irreplaceable, and is the largest of three distribution conduits to be used by the Strategic Petroleum Reserve. Capline plus TAPS ship 2.4 Mb/d of crude--nearly a fifth of all U.S. refinery runs.

Colonial, Tapline, and other U.S. pipelines have been and probably still are startlingly vulnerable to sabotage. In findings reminiscent of the state of nuclear-plant physical security in the mid-1960s, GAO found appalling laxity--and little managerial consciousness of sabotage risks [GAO 1979:30]--at many key pipeline facilities. The main Capline input terminal, for example, described by a company official as a most critical facility, had a catwalk that went over the fence from a public road to the building housing computer controls for the entire Capline system; entry to the building was uncontrolled during the day, and only a locked door protected the computer itself. Both Capline and Colonial pumping stations have even been burglarized by juveniles--who, fortunately, did not damage or misuse the equipment. Access to many key plants was uncontrolled or poorly controlled. Communications and backup power were poor: a major Colonial input station rated at 1.3 Mb/d peak, for example, had both its main and backup power transformers accessible and near each other [*id.*:29]. "Why there is a total lack of security around such [an electrical] installation...is almost beyond comprehension." [Stephens 1974:91] Simply reducing from afar the line voltage supplied to a facility's motors or electronic systems can cause damage that takes months to repair [*id.*; GAO 1979:23].

Many supposedly complementary pipelines parallel each other so closely that in practical effect they are colocated and co-vulnerable. "Some major crude and product lines are extremely close to each other as they extend from Texas and Louisiana...northeast....Damage at certain locations...could stop the flow of most of the gas and petroleum products now being delivered to the eastern U.S." [Stephens 1973:iv] "The fact that [the Colonial and Plantation]

systems come together at a number of points in their [parallel] route is a built-in weakness from a vulnerability point of view. A nuclear attack focused at or near certain areas of interchange between lines could create a major disruption of the major portions of the entire system. A view of a pipeline map shows flexibility at the intrastate level. It is possible for one pipeline system to sell to another locally. But, once the product is discharged into the interstate system, there is a considerable lack of flexibility." [id.:58] Further, the buffer stocks of oil downstream of pipelines are generally too small to cope with the duration of interruption that would be expected if an interchange, pumping station, input terminal, river crossing, or control system were damaged (that is, months rather than days). Average refinery crude stocks are about 3-5 days [Stephens 1979:208]. Typical Colonial receivers' market stocks are also in the range of 5-10 days [id.], and a two-week interruption of service in 1973 when difficulties arose in repairing a break in a remote area of Texas "became critical for many Colonial shippers" [id.:38].

Sabotage of oil pipelines is nothing new. The first screw-coupling pipeline introduced into the Pennsylvania oilfields in 1865 was dismantled at night by competitive teamsters [Congressional Research Service 1977:I:162]. In recent years, as pipeline bombings have become relatively common in the Mideast, they have started to occur more regularly even in the U.S. A Shell gasoline pipeline in Oakland, California was damaged in 1969, a Puerto Rican pipeline in 1975, and TAPS (as mentioned earlier) in 1977 and 1978 [Energy & Defense Project 1980:16]. A compendium of bombing incidents [GAO 1978:II:App.IX] lists the December 1974 dynamite bombings of 20 natural-gas transmission lines (2" to 20") and two natural-gas cooling towers in Kentucky; the September 1975 bombing, using crude high explosives, of two 5000-barrel oil storage tanks in California (fortunately, the barrel nearest the bomb contained only water); the discovery of a live military mortar round at an oil company facility in New York City in 1977; and the bombings of oil-company buildings in Pittsburgh in 1974 and in San Francisco in 1975. Should social tensions, fanaticism, or surrogate warfare by foreign powers again focus on oil pipeline facilities, whether through the violence of explosives and the like or by as simple a means as turning valves (most of which are readily accessible [Congressional Research Service 1977:III:163]), there is certainly plenty of opportunity to expand that list--which is itself probably far from complete.

Natural gas (and LPG) pipelines have broadly comparable vulnerabilities, plus the disagreeable feature that air "makes a 'bomb' out of the line containing an explosive mixture" [Stephens 1974:v]. Compressor stations, spaced every 40-200 miles (65-325 km), typically use gas turbines--inefficient but rugged--

fueled by the gas itself, an improvement over oil pipelines' frequent reliance on electric motors. (The compressor stations consume some 3-5% of the gas carried: pumping for oil and gas pipelines is a major energy user, probably consuming more than the total used in the U.S. by either water heating or aircraft.) Gas compressor stations, like their oil counterpart, are "virtually unguarded. There is little or no standby equipment....The system can be easily damaged. It is highly vulnerable to almost any hazard either man created or natural. Repair to a damaged segment could take months." [Stephens 1974:v] Most lines automatically detect breaks, isolate their sections (generally shorter than the 50-mile average interval between compressors, as there are also valves at each junction and elsewhere), and turn off compressors if necessary. There is little protection, however, for the control and communications links tying all the valves and compressors to a computerized central dispatching system. Stephens [1973:34] notes that because of the total reliance on remote telemetry and controls, "cutting of wires or destroying radio [or microwave] facilities could cause considerable confusion." With widespread disruption of communications "the system could become completely useless." Further, "The operation of complex pulse-time-modulation multiplex micro-wave equipment, telemetering equipment, facsimile units, automatic control systems and voice communication is the responsibility of the communications engineer. In a large terminal area, the engineer might have an assistant or two but as a general rule, one man has responsibility for the equipment over a very large area.... [I]t is doubtful that a replacement engineer could come into an [extensively] damaged complex system and make much progress in its early repair....The loss of [key personnel]...could cause very significant problems, even though equipment may not be seriously damaged. Even small repairs by one not knowledgeable of the [particular] system can become a major problem." [Stephens 1974:45]

Gas systems have a further point of vulnerability with no strict oil analogue: the "city gate" station where incoming pipeline gas is metered, odorized, and pressure-regulated. This last function is crucial, since pipeline pressures are vastly greater than retail distribution and end-use pressures. "Should one substantially increase pressure on the [43 million [Atallah 1980]] service lines serving residences and public buildings, the lines and/or appliances could rupture and the escaping gas could cause fires and explosions.... Careful pressure regulation is required in order for gas to be safe." [Stephens 1974:46] Conversely, pressure reductions, besides putting out pilots (p. 51), can cause damaging frost heaves near the regulator outlet pipe [Atallah 1980].

This ability to wreak widespread havoc by remote control has no parallel downstream of oil pipelines. Although the thousands of primary and tens of

thousands of secondary oil terminals are vulnerable to sabotage [Stephens 1973: 112], and local oil transportation can become a target--as when Japanese opposing Narita Airport firebombed a train carrying jet fuel to it [Los Angeles Times 1981d]--such targets, unlike LNG and LPG cargoes, are unlikely to cause more than locally severe damage unless they endanger some larger target, such as a refinery, tank farm, or reactor, near the site of attack. Compared to the natural gas system, with its virtually complete reliance on pipelines and its relatively limited storage, even the vulnerable oil system--with its dispersed and diverse routes, and with widespread buffer stocks spotted throughout the local distribution system--seems relatively resistant to disruption [Lerner et al. 1967; Grigsby et al. 1968; Boesman et al. 1970].

Perhaps compensating for the extra vulnerability of pressure regulation, gas grids appear to offer better opportunities than oil pipelines for rerouting. The Congressional Research Service [I:16] remarks that "In the last ten years, many additional interconnections have been added, to the point that, according to industry sources, there is hardly a crossing between two pipelines without an interconnection that could be used if needed. Compression might or might not be needed at interconnecting points to effect deliveries from a line operating at lower pressure than the receiving line, but in general, the technical problems of transferring natural gas within the pipeline network are reportedly not overwhelming. From a practical standpoint, the United States has a natural gas pipeline 'grid' which could be used to modify the directions and quantities of natural gas flows substantially." How far this would remain true if key interconnections or control systems were disrupted is open to considerable doubt, and Stephens [1979:213] says the interstate grid is fairly inflexible anyhow. Nonetheless, processed natural gas, unlike oil (crude or specific products), is a relatively homogeneous commodity fungible within the grid.

A recent trend accompanying higher oil and gas prices highlights the vulnerability of their grids: the prevalence of theft, ranging from the hijacking of a 25,000-gallon tank truck to the theft of hundreds of thousands of gallons from Wyoming fields. "Oil thefts have occurred in every major U.S. port, notably in Houston and New Orleans, where tankers at anchor have been tapped. Gasoline has been siphoned out of storage tanks in New York, Philadelphia and Baltimore. Barges carrying jet fuel, gasoline and heating oil on the Mississippi River have been robbed." In major refineries in the Southwest, "there is evidence that organized crime may have infiltrated" and the FBI has assigned undercover agents. The FBI is "spiking" crude oil shipments with chemicals so stolen shipments can be traced [O'Toole 1981]. Further, "The technology for tapping into a pipeline, even a high pressure natural gas pipeline, without causing a leak, explosion, or other major incident revealing the existence of the tap, is published and well-known. In 1975, the FPC [Federal Power Commis-

sion] reported 140 billion cubic feet of natural gas as unaccounted for, about half of which was lost during transmission. This gas, which was shown on meters entering the system, but was neither sold to customers, placed into storage, or used in compressors,...[was worth at 1975 prices] \$110 million. A portion of it may well have been stolen." [Congressional Research Service 1977:III:165] Clearly, people knowledgeable enough to steal large amounts of oil and gas from tankers, pipelines, tanks, etc. are also able to cause serious harm to those systems if they are so minded.

In short, by increasing its reliance on a highly engineered, inherently vulnerable oil and gas system designed for a world of infinite tranquility, the United States has reached the point where a handful of people in a single night could stop over 75% of gas supplies to the Eastern U.S. for a year [Kupperman & Trent 1979:73] without ever leaving Louisiana. With a little more travelling, they could cause lasting havoc in the oil system too. This is a function not only of where the oil and gas come from--nearly three-fourths of total marketed U.S. gas extraction, for example, is in Texas and Louisiana--but also of the nature of the processing and distribution technologies, which is an expression of the nature of the fuels themselves.

It is encouraging that many new oil and gas discoveries are highly dispersed, especially in traditional importing areas [e.g. Byron 1981; Pennino 1981], and that this might reduce dependence on long-distance pipelines--a goal Stephens recalls was once met with dispersed town-gas plants [1974:80]. But at the same time, the proposed massive program of synthetic-fuels development, chiefly from Western coal and shale, would add profound new vulnerabilities, as the processes not only must deliver their products by long pipelines, but also depend on enormous deliveries of water, power, and feedstock, often from far away. Supplying 10% of present U.S. oil use would take 90 \$2-billion plants, using half of all U.S. coal mined in 1978 [Taylor 1980:309]. In 1944, Allied bombing around the Ruhr reduced German synfuel output by more than 90% (from nearly 100,000 b/d) in a few months, hobbling the Nazi war machine [Energy & Defense Project 1980:22-24]. (Earlier, a single raid on 1 August 1943 had destroyed 350,000 barrels of oil and half the refining capacity in the Romanian oilfields at Ploesti, then a key German source.) It now appears, as noted above (p. 49), that earlier bombing of other German oil facilities, especially those making aviation fuel, would have curtailed World War II still sooner [SIPRI 1974:142-145]. In our own day we see fire and bomb attacks on South Africa's crucial SASOL synfuel facilities [Burns 1980]. These historical lessons do not bode well for the present or future dependence--either of America's 0.7 Mb/d military machine [Maize 1980] or of our civilian economy--on any centralized source of liquid fuels, natural or synthetic.

3.3. Central-electric systems.

The vulnerability of oil and gas terminals, processing plants, and pipelines is mirrored in central-electric systems--only worse. Electricity, though not itself flammable or explosive, is very difficult and costly to store in bulk. While the oil and gas systems contain at several stages extensive storage providing a "pipeline inventory" of weeks or months, the electric grid has no significant storage between plant and end-users (unless they have provided local storage or backup at their own substantial expense). Thus, in the event of supply or delivery failures, unless electric power can be rapidly rerouted--subject to the availability of generating and transmission capacity, of switchgear, and of control and communications capability--disruption is instantaneous and can be widespread. Further complications--the great complexity of maintaining synchronization, frequency and phase stability, and voltage stability, and the tendency of these requirements to complicate restoration after failure--were already surveyed in Chapter 2, and are markedly less tractable than the analogous problems of maintaining oil and gas purity and distribution pressure. The time constants of the electric system are also far shorter: control response is often required in milliseconds, not minutes or hours. Reliance on computerization, farflung telecommunications networks, and specialized skills--already cause for concern in oil and gas grids--is even greater in electric grids.

There are also close analogies in vulnerability. Chapter 2 noted that many key components of electrical systems, ranging from turboalternators to main transformers, are special-order items with long delivery times. Repair of substations and transmission lines has many features in common with repair of pipelines and pumping stations. Just as refineries depend on continuous supplies of cooling water, pump lubricants, etc., so do many costly electrical components. The analogies continue even to certain details: just as refineries, for example, have a risk of explosion from hydrogen used to hydrogenate carbon-rich molecules into light products, so big electrical generators too are often cooled with hydrogen (whose small molecules reduce friction). But perhaps because power failures are so much more immediate and dramatic than interruptions of oil or gas supply, and offer so few options of substitution in the highly specialized end-use devices, electrical grids and their components seem to be far more frequently sabotaged than oil and gas grids. This section, building on the introductory material in Chapter 2, will further examine the particular vulnerabilities which led the Comptroller-General [1981a] to find that sabotage of eight substations could black out a typical region, and that sabotage of only four could leave a city in that region with no power for days and rotating blackouts for a year.

3.3.1. Power stations.

About 12% of the domestically generated electricity supplied to U.S. grids comes from about 1200 hydroelectric dams, of which about 360 exceed 25 MWe. Most of the output currently comes from a small number of very large dams, although (as Chapter 7.3.2 will note) this is likely to change in the next few decades. Most dams and their turbines (though not their switchgear and transmission lines) are relatively resistant to interference--luckily, since destruction of a dam often carries a risk of serious flooding. About 1% of national installed generating capacity is in nearly a thousand diesel engines, mainly in rural areas and small peaking plants. Another 8% of the capacity is in about 1200 gas turbines, run on average only 7% of the time; their high fuel cost and low thermal efficiency restricts them to peaking use. About 0.1% is in geothermal and wind capacity. The remaining plants--about 78% of installed capacity, supplying about 82% of the kilowatt-hours--are the 900-odd major "thermal" (steam-raising) plants, operating on average at just under half their full-time, full-power capacity, and generating in 1979 about 55% of their output from coal, 15% from oil, 17% from natural gas, and 13% from uranium. (Since then the oil burn has fallen dramatically, from about 1.7 Mb/d nearly to 1 Mb/d in 1981, heading for 0.8 Mb/d or so by the end of 1982 [Taylor 1980a]. The main substitutes for oil have been coal and efficiency improvements.) These statistics do not include self-generation of electricity in factories. This "cogeneration" as a byproduct of process heat or steam, using combined-cycle steam turbines, diesels, or gas turbines, probably provides electricity equivalent to at least 5% of the electricity generated for the grid, and is often independent of grid operation, providing its proprietors with greater "insurance" (p. 52).

The large thermal plants supplying over four-fifths of U.S. grid electricity deserve special attention here, not only because of their centralization and dominance, but also because they need continuous provision of fuel, cooling water, outlets for their electricity and effluents, and control and communications systems. Interruption of any one of these will shut down the plant. (On-site fuel stocks, however, can provide a buffer of days to weeks for dual-fuel gas-fired plants holding oil stockpiles, one or two months for oil-fired plants, three months or more for coal, and one or more years for nuclear. Single-fuelled gas-fired plants, common in such regions as Texas [whose grid is not interconnected with the rest of the country], carry almost no stocks: Goen *et al.* [1970:75] found that San Francisco's entire gas storage capacity would last one local gas-fired power plant for only 14 hours.) Power plants' complex, special-purpose machinery itself is of course also vulnerable to disruption,

even by low-technology means: modern turboalternators, for example, are so big, yet so delicate, that when not spinning they must have their shafts rotated a fraction of a turn several times per hour, by hand if necessary, lest their own weight ruin them by bending the shaft out of true. On occasion, such as during the Three Mile Island accident, this service has been difficult to provide in the face of evacuation requirements.

The vulnerability of central thermal power stations is not a new issue. In 1966, the Defense Electric Power Administration [1966:13A] pointed out that "fewer than 200 cities and towns of over 50,000 population contain about 60% of the population and associated industrial capacity of the nation. The larger generating facilities tend to be located near[by]....Generating capacity is the most difficult, costly, and time consuming component of an electric power system to replace and also tends to be highly concentrated geographically. If any portion of the power system is to be considered a primary [strategic] target, it would be these large generating plants....Is the concentration of power generation making the industry more vulnerable....?"

In the intervening 15 years, the question has been often repeated, yet the concentration has increased, with major power plants being drawn to conurbations and probably encouraging urbanization and industrial concentration in their turn. "Although there are about 3,500 companies involved in generating and distributing electricity, about half of our total electrical capacity comes from fewer than 300 generating stations. Most of these are located in or near our major urban-industrial areas. The electric utilities therefore present a relatively compact and especially inviting set of targets for a saboteur, a terrorist or an attacker, as well as a lightning bolt." [Joint Committee on Defense Production 1977a:1] Though this concentration is less than that of some other sectors--pipelines, large refineries, smelters, etc. [Goen et al. 1970:71]--it is also uniquely true of power stations that the loss of substantial generation or transmission capacity can crash the whole grid, shutting down undamaged plants that are inadequate to maintain system frequency. The Research Director of the American Public Power Association was recently moved by these trends to remark [Holmberg 1981] that "there is considerable evidence that one of our highest national defense priorities should be to insure the continuity and productivity of the United States through aggressive support of decentralized energy supply." Confirming this, attacks on power stations have become almost a routine feature of guerrilla campaigns, ranging from Italy and Puerto Rico (as noted in Chapter 2.2.2) to Cyprus (1955), Britain (1969, by internal sabotage at Aberthaw and perhaps Fiddler's Ferry), Eire (1974), Chile, and El Salvador. After a California plant bombing, one power engineer told us

that the company had escaped with minor damage only by the saboteurs' lucky choice of the strongest point on the strongest station: electric plants, he said, are "terribly vulnerable. Someone who knew anything at all could cause terrible havoc." Other targets could easily have been "blown over."

3.3.2. Electrical transmission.

High-voltage transmission lines carry an astonishing amount of energy, second only to large pipelines. A 500-kV line typically handles about 2 GWe, the output of two giant power stations [Congressional Research Service 1977:I:357]; a 765-kV line, about 3 GWe. In some areas, such as New York City and South Florida [Joint Committee on Defense Production 1977a:7-8], geography squeezes supposedly independent transmission lines into a single narrow corridor. In others, remotely sited plants, perhaps at a Western coal-mine, send their lines over hundreds of miles of remote countryside. No transmission line can function without switchgear and controls at each end: the entire New York-New England power pool, for example, is controlled from a single center near Schenectady [Joint Committee on Defense Production 1977:II:36]. Broadly speaking, the contiguous U.S. grid is interconnected within each of three largely separate regions [Congressional Research Service 1977:I:365]--Texas, eastern, and western, with the demarcation running roughly through Nebraska--but interchange between the constituent pools of each region is heavily dependent* on particular transmission segments, such as the 7-GWe Wisconsin-Missouri-Illinois intertie [Metz 1977], as well as on the pool and utility control centers and communication systems and on uniquely vulnerable extra-high-voltage switchgear and transformers [Kupperman & Trent 71-72,106]. Despite their key role in interstate commerce, transmission lines are in general not protected by Federal law [Joint Committee on Defense Production 1977a:8].

Transmission lines have often been sabotaged. Examples cited by the Energy & Defense Project [1980:16] include New Jersey 1978, Colorado (lines feeding a military plant) 1969, and California 1975. Fourteen towers in Oregon were bombed, and at least six toppled, in 1974 by an extortionist threatening a Portland "blackout"; pipe bombs caused minor damage at six California towers in one night in 1975 [GAO 1978:II:App. IX]. Other attacks include Alabama 1966, Ohio (blacking out parts of Cincinnati) and Louisiana 1967, Wisconsin 1968, and California and Washington 1973 [Flood, personal communication]. In the bitter confrontation mentioned in Chapter 2.1.3, conservative, fiercely independent Minnesota farmers during 1979-80 caused \$7 million in damage to an 800-kVDC line. No "rat weevils," having perfected a low-technology

*For examples, see [Economic Regulatory Administration 1979:II:181-216].

technique requiring only a few people and hand tools, have toppled 14 towers, and an outbreak of "insulator disease," commonly ascribed to rifles (or even to sophisticated slingshots), has littered the ground with the remains of over 8,000 fragile glass insulators. The epidemic attacked 350 insulators per week in early 1979--sometimes more than that in a single night [Casper & Wellstone 1981:283,285]. The 1.5" aluminum wires themselves proved vulnerable to rifle fire [*id.*:277]. Guarding just the Minnesota section of line--176 miles with 685 towers, often through farmers' fields far from public roads--is still, at this writing, proving an impossible task. Despite high-speed helicopters, a \$100,000 reward, 300 private guards, and extensive FBI activity, not one of the perpetrators has been caught. It is no more likely that they will be, given the depth of their local support, than that South Africa will discover who has, as we write this, cut its power lines from the Cabora Bassa dam in Mozambique, threatening South Africa with "selective power cuts" [*Los Angeles Times* 1981e], and blacked out Durban by blowing up a substation [*id.*:1981g]. No wonder an Interior Department expert confirmed that "a relatively small group of dedicated, knowledgeable individuals...could bring down [the power grid supplying] almost any section of the country," or "a widespread network" if organized on a somewhat broader scale [Joint Committee on Defense Production 1977a:87].

Even without interference, transmission lines are vulnerable enough. Of the twelve worst interruptions in U.S. bulk power supply during 1974-79, six were caused by failures in transmission, six in distribution, and none in generation. Seven were initiated by bad weather, four by component failures, and one by operator error. [Economic Regulatory Administration 1981:4-4] Among all reported interruptions during 1970-79, however, "75% have been due to problems related to facilities, maintenance, or operation and coordination. Only 25% have been initiated by weather or other forces external to the utility" [*id.*: 4-5]. Whatever the causes, failures are rife. On 5 April 1979, a buildup of dust and salt spray on 240-kV insulators caused arc-over, leaving no outlet for three generating stations and blacking out the Miami area and much of Fort Lauderdale and West Palm Beach [*International Herald Tribune* 1979]. The Québec transmission grid averages about three major failures per year, chiefly in cold spells which (owing to the intensive promotion of electric heating) coincide with peak demand. In the chilly first week of January 1981, both Hydro-Québec and Ontario Hydro met record peak loads only by importing power: the former had lost nearly 2 GWe through transformer failure at the James Bay hydro site, and the latter, about 1.5 GWe through emergency shutdowns at two nuclear plants and a coal plant [Claridge 1981]. On 8 January 1981, a sudden power failure, apparently due to a quadruple transmission failure, blacked out all of Utah and

parts of Idaho and Wyoming for 3-6.5 hours--some 1.5 million people in all [New York Times 1981]. On 24 September 1980, most of Montana was blacked out for about an hour, prompting editorial comment on the vulnerability of "Society's electric heartbeat" [Great Falls Tribune 1980]. Both these regions are of special interest because they are officially planned to become--via coal mines, coal slurry pipelines, and synfuel plants, all of which are extremely dependent on reliable electric supplies--a main source of domestic fuel to replace Mideast oil. In various parts of the country, transmission lines have been interrupted by aircraft accidents (a National Guard helicopter crashing into a 161-kV TVA line in 1976), explosions, equipment faults, broken shield wires (which run from the apex of one tower to the next), and even kite flying [Clapp 1978:41]. Southern California Edison Company has experienced extensive damage to 16-kV and smaller wooden-poled lines (though little to >22-kV lines on steel towers) through forest fires; and on occasion, the fiery heat has ionized the air sufficiently to short out conductors [Chenoweth et al. 1963:34].

3.3.3. Substations and distribution networks.

Transmission is usually considered to involve lines carrying at least 69,000 volts (69 kV), and bulk power transmission, over 230 kV [Congressional Research Service 1977:I:349]. "Main transmission lines are extremely difficult to protect against sabotage as they are widespread over each state and traverse remote rugged and unsettled areas for thousands of miles. While these facilities are periodically patrolled, ample time is available for a saboteur to work unobserved. It may be comparatively easy to damage this part of a system, but it is readily repaired. Damage to remote controlled or automatic substation equipment could make repairs and operation more difficult." [Defense Electric Power Administration 1962:25-26] The analogy with pipelines is clear enough: the line, save in especially awkward locations, is far quicker to repair than its interchanges and operational systems (pumping stations for pipelines, substations for electric transmission). A principal point of vulnerability, albeit one seldom capable of blacking out more than a relatively local area, is the substation which transforms transmission to lower voltages for distribution over subtransmission lines and over 4 million pole-miles of retail distribution lines [Defense Electric Power Administration 1969]. Although DEPA [1962:26] considers that damage to substations and distribution networks "would have such a slight effect on the overall system as to make this type of sabotage unlikely", many saboteurs evidently do not see it that way. There are over four times as many substations rated over 10 MVA as there are central

power stations [Goen et al. 1970:79], so near virtually any load center there is a corresponding substation--an effective target for highly selective blackouts or a convenient one for symbolic damage. Both transmission substations (serving mainly large industrial customers at subtransmission voltages) and distribution substations (serving mainly residential and commercial customers) have been attacked by many means. In 1975 and 1977, the same Pacific Gas & Electric Co. substation was damaged by pipe bombs, interrupting tens of thousands of customers [Joint Committee on Defense Production 1977a:61]. Four other PG&E substation bombings caused local blackouts in 1977, and a transformer bombing blacked out eastern Puerto Rico in 1975 [Energy & Defense Project 1980:16]. Additional substation and transformer bombings occurred in California and Seattle 1975, Colorado (causing \$250,000 damage) in 1974, Albuquerque in 1977, and two California sites in 1977 [GAO 1978:II:App.IX]. During 1974-77, the FBI reported a total of 10,919 actual or attempted bombings in the U.S., of which 82% (5273 explosive and 3686 incendiary) were successful. Although public utilities represented only 1.9% of the total targets in 1975-76, they did suffer 53 deliberate explosions in that period--about one every two weeks [id.]. In some instances, such as the Oregon transmission-line bombings in 1974, the campaign was so concerted that a massive investigation and manhunt were deemed necessary [Congressional Research Service 1977:III:159]. To complicate matters, utility transformers often contain cooling oil that can be released and ignited by standoff methods, including rifle fire; the oil may contain highly toxic PCBs, which greatly complicate repairs; and hard-to-trace disruption can be caused simply by using the substation's controls without damaging them. (A novel [Chastain 1979] describes a fictional extortionist who caused blackouts in New York City by throwing under-street transformer switches.) Con Ed's Indian Point substation even caused a blackout 19 July 1977 when it blew up all by itself; a similar incident on 12 July 1981--one of three Con Ed substation fires in five days--blacked out 39,000 customers [Gargan 1981]. A recent failure at a single 69-kV transformer blew it up, ignited 3000 gallons of cooling oil, and halted the supply via 13 underground cables to two substations, blacking out for four hours 6% of Con Ed's load--much of lower Manhattan, including one of the world's densest concentrations of financial computers [Kihss 1981,1981a].

To the end-user, it matters little whether a power interruption is in the bulk supply--which accounts for only about 15% of the total--or in distribution (the other 85%) [Economic Regulatory Administration 1981:4-10]. The roughly 365,000 circuit miles of overhead transmission [id.:2-9] and its switchgear and control systems are a tempting target for widespread disruption; but for local or selective disruption, sabotage of distribution is at least as easy to arrange and at least as hard to repair, with the added bonus that alternative distribution (unlike transmission) routes are often not available unless the utility happens to have suitable mobile equipment that can be spliced in temporarily.

3.3.4. Control and communications.

No part of the synchronous electric grid can function without continuous communications from such centralized, computerized control points as utility and pool dispatchers to each other and to the field. The vulnerability of field hardware to nuclear attack [Chenoweth *et al.* 1963; Lambert 1976] pales beside control vulnerability to the 10-nsec-risetime electromagnetic pulse (EMP)--peaking at 50 kV/m and 6 MW/m² (6000× the power density of peak sunlight)--produced by a 1-MT high-altitude thermonuclear burst over a radius of 800 km or more [Lerner 1981:42]. Thus one blast high over the central U.S. would blanket all lower 48 States with a pulse of at least 25 kV/m [King *et al.* 1980]--ample to cause an instantaneous common-mode failure of unhardened electrical and electronic systems, including electric-grid and pipeline controls, telephones, and other telecommunications except fiber optics. Most grid controls would be damaged functionally (burned-out transistors) or operationally (erased computer memory) [Lambert 1976:51; Lerner 1981:42ff]: integrated circuits are about ten million times as prone to EMP burnout as vacuum tubes [Broad 1981]. Since power lines act as antennas to collect the pulse, and its risetime--a hundred times faster than lightning--is too fast to be stopped by most lightning arrestors, many end-use devices would probably be burned out. Such non-control devices as transformer windings and transmission-line insulation could also be damaged by peak induced surges as high as 30 GW [Lerner 1981:42ff]. Nuclear reactor safety systems may be disabled [Energy & Defense Project 1980:305], perhaps causing an epidemic of meltdowns [Lerner 1981a]. Design trends in the power industry are tending to increase the likelihood of EMP damage [Nelson 1971], and "the extreme difficulty and expense of protecting the grids has discouraged utilities from taking virtually any action" [Lerner 1981:46].

The power grid's control and communication are vulnerable to commoner hazards than EMP. "Because of their vital role in system reliability, the computer facilities in control centers are usually doubly redundant (backed up by a complete set of duplicate facilities); in at least one center they are triply redundant. Their power supplies are 'uninterruptable' and are also often doubly redundant." [Econ. Regul. Admin. 1981:2-8]. Yet a pocket magnet, as Stephens points out, can give a computer amnesia. Grids' ability to reroute power [Lambert & Minor 1975] assumes the perfect operability of control systems. Control centers, furthermore, must communicate with each other and with field equipment (generators, switches, relays, etc.); otherwise no rerouting or load alterations are possible. This communication relies on telex, telephone, signals sent over the power lines themselves, radio, and private microwave circuits. Despite battery and standby-generator power supplies, all these links are vulnerable to disruption. With microwaves, for example, "the loss of one base or repeating

station can easily make a large portion of the communication system inoperable" [Defense Electric Power Administration 1962:31]. Most utility operations can probably be disrupted far more easily by attacks on their communication systems than on generation, transmission, or distribution components. Without instant communication, or at least an army of experts in the field manually operating the system according to prompt radio instructions, the stability of the grid will be in danger. Few utilities have installed reliable underfrequency relays to ensure that if control and synchronicity are lost, their grid will automatically isolate itself into small islands, maintaining service where possible and at least preventing serious damage to major components.

Another disturbing possibility, to which no attention appears to have been given, is that rather than merely cutting communications, a saboteur might--like a phone phreak--prefer to use them. Indeed, both private and public telephone lines can be tapped into remotely, as noted in Chapter 1.2.4, and many utilities' control computers--not merely their accounting computers--appear to be accessible to phone phreaks. Such codes as are normally used are easily broken by the phreaks' microcomputers. Worse still, despite the encryption used on some utility microwave networks, it is probably well within many electronic enthusiasts' capabilities to tap into a utility microwave net using a portable dish and effectively to take over the grid.

One utility control expert with whom we discussed these concepts felt that the diversity of communications links which his company uses, and certain technical features of its microwave and other systems, would make takeover difficult: most likely the company's operators could still maintain control. But he agreed that this result, if true, was not by design but by accident--a result of precautions taken against natural disaster--and that companies less sophisticated than his own (perhaps the best-prepared in the country in this regard) might well be worse off. That particular grid is designed to be manually operable from dispersed control centers, but it is not hard to envisage ways in which communications between them could be blocked or spoofed, and the grid perturbed, in ways beyond the ability of manual control to handle. For most if not all electric utilities, elementary consideration of the published details of communication systems suggest that the vulnerabilities commonly discussed--such as the risk of sabotage to switchyards, transmission lines, and power plants--are just the tip of the iceberg. Analogous considerations apply to the control and communications systems of oil and gas pipelines.

In summary, whether by brute-force sabotage of a key switching or transmission facility or of one of the operational lifelines (such as cooling water or fuel transportation) of one or more giant power plants, or instead by an

elegantly economical disruption of control and communications systems, a small group of people--perhaps one able person in some circumstances--could black out practically any city or region. With careful selection of targets and of their most vulnerable times (peak loads, options limited by preexisting outages, unfavorable weather for repair, etc.), it should not be beyond the ability of some technically astute groups to black out most or all of any of America's three synchronous grid regions. These blackouts can be engineered in such a way as to cause substantial damage to major items of equipment, probably requiring months or years to repair. It is conceivable that similar breakdowns could arise from a combination of natural disasters, imperfect utility response, and incomplete understanding of the operational dynamics of big grids. However caused, a massive power-grid failure would be slow and difficult to restore, would gravely endanger national security, and would leave lasting economic and political scars.

3.4. Nuclear fission systems.

Nuclear power reactors* suffer from the vulnerabilities already described for central-electric systems. This section explores the following additional, uniquely nuclear vulnerabilities of reactors and their ancillary plants:

- their enormous radioactive inventories, which may be a focus for civil concern and unrest [Ramberg 1978], an instrument of coercion [Norton 1979], and a cause of devastation if released by sabotage or war;
- their unusual concentration of interdependent, exotic resources; and
- their facilitation of the manufacture of nuclear bombs.

*For simplicity, this treatment will consider only fission reactors, not potential future fusion reactors (which would have analogous but milder safety and waste problems and several significant safeguards problems.) Power reactors will be assumed here to mean those commonly used in the U.S.--light-water reactors (LWRs)--rather than other thermal-neutron reactors such as CANDU or fast-neutron reactors such as the proposed liquid-metal fast breeder. For the purposes of this discussion, these design distinctions do not give rise to important differences of principle. Our conclusions do not depend on differences between once-through and reprocessing fuel cycles, and although the former is likely to remain the U.S. commercial practice, we briefly consider the potential for major radioactive releases from reprocessing plants.

The likelihood of releases from sabotage of large power reactors may be similar, and the consequences roughly equivalent, in the case of numerous small teaching and research reactors, since they are often in the middle of large cities, take few or no security precautions, and have no containment buildings. For simplicity, these small reactors will not be described further here, but a complete analysis would have to consider them more fully. A more comprehensive and documented treatment of technical issues raised in this discussion can be found in [Lovins & Price 1975; Lovins & Lovins 1980]; see also [Ford 1981].

We ignore here certain Federal nuclear facilities, damage to which could have serious national-security consequences [IEAL 1980:1:2-10f].

This analysis concentrates on the first of these three vulnerabilities, and especially the extent to which nuclear facilities can provide an attractive target for sabotage or acts of war. The large literature on major hypothetical releases of radioactivity deals almost exclusively with accidental releases, which are often claimed to be very improbable. That analysis tends to ignore intentional releases, although it is common ground that the consequences of a major release by either cause could be unprecedentedly grave. The Atomic Energy Commission's Director of Regulation agreed [Dye 1973], for example, that a band of highly trained, sophisticated terrorists could conceivably destroy a near-urban reactor so as to cause thousands, perhaps even millions, of deaths. More recently, his NRC successor agreed [Subcommittee on Energy & the Environment 1977:8] that "thousands of lives and billions of dollars" could be lost. Because these consequences are so great, it is important to establish whether nuclear terrorism and sabotage are plausible, what sorts of people and weapons might be devoted to that end, and what technical vulnerabilities of nuclear plants might be exploitable. We shall therefore consider these subjects in turn before returning to examine in more detail the consequences--radiological, social, and economic--of such acts. This section will conclude with a brief survey of the special problems of illicit nuclear bombs.

3.4.1. Nuclear terrorism: intentions and incidents.

Whether nuclear terrorism is plausible is best inferred, not only from a study of the technical potential for it, but from what terrorists have said and done. Low-level attacks on nuclear facilities have in fact become so common, and the level of violence is escalating so steadily [Bass *et al.* 1980:77], that it seems only a matter of time before major attacks are successfully attempted.

International terrorists are directly reported to be showing an increasing interest in nuclear matters. A Europe-wide NATO alert shortly after the assassination of Aldo Moro "was prompted by an explicit warning from the West German state security officials of possible terrorist plans for atomic blackmail: raids on nuclear bomb depots, kidnapping of specialized NATO officers, hijacked raw materials, occupation of nuclear plants, to name a few possibilities in what the Red Brigades speak of as 'a growing sensitization to international security objectives.'" [Sterling 1978:38].

In a clandestine interview with Stern [Kellen 1979:61-62], defected German terrorist Michael Baumann stated, "I do not want to suggest that some group, at this time [1978], has concrete plans or even definite plans [for nuclear extortion]....But nevertheless, this is in the spirit of the times" and has been

discussed among terrorists. As governments harden their no-concessions policy against terrorism, terrorists are driven

...to do something that will work for sure, and what else can that be except the ultimate thing? Q. Could that mean that they might occupy a nuclear power station? A. Sure. These are intelligent people and they have vast amounts of money. They also can build a primitive nuclear bomb. But an attack on a storage depot is more likely. After the killings in Lebach, the Americans noted that in a barracks 16 half-forgotten nuclear warheads were stored. Only a few German guards were there with their police dogs. Q. And how would the...terrorists proceed in the course of a nuclear action? A. That is, initially, completely without importance. Anyone who has something like that [nuclear weapons] in hand has enough power to make the Prime Minister dance on a table in front of a T.V. camera. And a few other statesmen alongside with him. That is an I.O.U. of ultimate power.

While Baumann's statements are somewhat speculative and cannot be taken as a definitive indication of the intentions of today's hard-core terrorists, they are nonetheless a useful starting-point for further inquiry.

More indirect motives might also be important [Bass et al. 1980:6]:

Given that leftist radicals see nuclear programs as symbols of a corrupt, militarist, capitalist state, they may attempt violent actions against nuclear targets as a way to rally opponents of civilian or nuclear nuclear programs to their cause. European terrorist groups clearly have identified the antinuclear movement as a source of possible supporters and have carried out actions calculated to appeal to the more extreme members of that movement [who would, however, be rejected by their colleagues, the overwhelming majority of whom adhere to the principles of nonviolence].... [I]t has been reported that in Italy a Red Brigades document urged attacks on nuclear power plants to exploit antinuclear sentiment in the country.

Has this interest actually been manifested in overt acts of sabotage and terrorism against nuclear facilities? Unfortunately, the list of such incidents is already long and is growing rapidly. The perpetrators seem no longer to be limited to isolated individual saboteurs and local semi-amateur groups, but increasingly to include more organized and sophisticated international groups with access to a worldwide network of resources. In two instances, an Iraqi "research" reactor has been overtly attacked by government aircraft as an act of war, the second time being destroyed. But lower-level, clandestine episodes abound. The following list of published incidents (plus the other examples postponed to later sections) give the flavor of the diversity and the gradually escalating intensity and focus of nuclear terrorism to date. (Incidents not specifically documented are generally given in Flood's compendium [1976].

- Armed attacks and bomb explosions. The Atucha-1 reactor in Argentina, when nearly built in 1973, was taken over by 15 armed guerrillas for publicity. They quickly overpowered five armed guards, caused only light damage, and wounded two other guards whom they encountered while withdrawing [Burnham 1975: 32]. The Trojan reactor in Oregon has had its Visitor Center bombed [Kupperman

& Trent 1979:36]. The Fessenheim reactors in France sustained peripheral site damage by fire after a 3 May 1975 bombing. On 6 June 1975, half the input terminals at the computer center of Framatome (the French reactor vendor) were destroyed by a carefully placed bomb, and another damaged valve testing shops in Framatome workshops. Two bombs set by Breton separatists on 15 August 1975 caused minor damage to a cooling-water inlet and an air vent at the operating gas-cooled reactor at Monts d'Arée, Brittany, which was closed for investigation; it was the eighth sabotage attempt in a month by the separatists against utility installations, and the most spectacular, using a boat that crossed the artificial cooling lake through cut fencing. In early November 1976, a bomb caused extensive damage at the Paris offices of a nuclear fuel manufacturer, and two more put a French uranium mine out of operation for about two months by destroying four pump compressors [de Leon et al. 1978:29]. In March 1978, Basque separatists bombed the steam generator of the Lemoniz reactor, under construction near Bilbao in northern Spain, killing two workers, injuring 14, and causing heavy damage [Bass et al. 1980:11], as part of ten simultaneous attacks on scattered facilities of the plant's construction company, Iberduero [Times 1978]. By 1981, the project was under siege [International Herald Tribune 1981]: its chief engineer (like the manager in 1978) had been kidnapped*, Iberduero had been bombed again (killing the fourth bomb victim in three years' attacks), and more than a dozen bomb attacks on Leminoz and Iberduero had occurred in January 1981 alone. "There have been armed assaults on nuclear facilities in Spain, and armed terrorists recently broke into a nuclear facility in Italy." [Bass et al. 1980:74] Unknown saboteurs skillfully blew up the nearly completed core structures of two Iraqi "research" reactors at a French factory on 6 April 1979. Electronic controls at the Stanford Linear Accelerator were heavily damaged by two bombs in 1971. Reactor guards at several U.S. sites have been fired upon [e.g. Subcommittee on Energy & the Environment 1977a:247]. On the 1976 Memorial Day weekend, the USNRC issued a security alert to U.S. nuclear plants on the basis of "highly tentative and inconclusive information" the nature of which has not been disclosed [Los Angeles Times 1976]. Unexploded bombs have been found at the Ringhals reactor in Sweden [de Leon et al. 1978: 29], the Point Beach reactor in Wisconsin in 1970, and the Illinois Institute of Technology reactor in 1969. In 1975-76, a person "was arrested for attempting to illegally obtain explosives to use in sabotaging a [U.S.] nuclear power-plant" [Comptroller General of the U.S. 1977:2]. The chief scientist of the Iraqi nuclear program was recently assassinated in Paris (as was a probable witness), allegedly by Israeli agents [Marshall 1980a]. "Terrorists in Spain have kidnapped officials of nuclear facilities for the purpose of interrogating them

*He was later killed [Toth 1981].

and taking their keys to place bombs in their offices. The same [Basque] terrorist group has threatened prominent officials in the nuclear industry with assassination if planned nuclear programs were pursued. Terrorists in West Germany have placed bombs at the homes of those charged with the security of nuclear facilities." [Bass et al. 1980:74]

- Insider sabotage. A 1971 fire doing \$5-10 million damage to the Indian Point 2 reactor in New York was set in an auxiliary building (housing control panels, cables, and pumps) while Unit 2 was fueled but not yet critical and Unit 1 was operating nearby. The arsonist turned out to be a mechanic and maintenance man at the plant, had worked for Con Ed for seven years, was an Army veteran, was married with three children, had long lived in the area, turned in the alarm himself, and was among the first to fight the fire [Bass et al. 1980:40]. "A series of suspicious fires between June and November 1977 delayed the completion of Brazil's first nuclear power plant at Angra dos Reis." [id.] Worker sabotage has been reported at Zion in Illinois in 1974 [Emshwiller 1980a], at the Fort St. Vrain high-temperature gas-cooled reactor in Colorado, at the Trojan reactor during its construction in Oregon in 1974, at Browns Ferry in Alabama in 1980 (reportedly including the disabling of closed-circuit TV cameras) [id.], and in Switzerland [Bass et al. 1980:74]. During a 1973 strike against Florida Power & Light Company, there were 101 incidents of sabotage damaging equipment offsite, and the FBI was alerted to a rumored plan to sabotage the main generator at the Turkey Point nuclear plant. Suspected arson has occurred at Knolls Atomic Power Laboratory (General Electric, New York), at several other U.S. nuclear research facilities, and in 1975 in an equipment storage barn at the West Valley (New York) reprocessing plant. The Winfrith, Wylfa, and Berkeley reactors in Britain have been damaged by sabotage during construction or operation--Winfrith by pouring a mercury compound into the calandria, where it amalgamated with the aluminum alloy, causing serious damage. Two control-room workers at the Surry reactor in Virginia were convicted in October 1979 of causing \$1 million damage to 62 unirradiated LWR fuel assemblies by pouring lye over them "to bring public attention to what they described as lax security and unsafe working conditions at the plant" [New York Times 1979]. Numerous nuclear facilities of all kinds received threats, usually bomb hoaxes; during 1969-76, licensed nuclear facilities recorded 99 threats or acts of violence in the U.S. (76 of them at federal plants), with 23 analogous threats at government nuclear plants in the U.K. By 1979-80 the U.S. list had expanded to over 400 incidents, 350 of which were telephoned bomb threats to nuclear facilities [Bass et al. 1980:53]. The list omits nuclear-related military incidents--such as 11 cases of arson in three months, killing

one worker and injuring over 30 sailors, aboard the nuclear-capable aircraft carrier John F. Kennedy, perhaps set by a sailor seeking to delay her sailing [id.:43].

- Breaches of security at nuclear facilities. In 1966, 20 natural-uranium fuel rods were stolen from the Bradwell reactor in England, and in 1971, five more disappeared at or in transit to the Wylfa reactor. In 1971, an intruder wounded a night watchman at the Vermont Yankee reactor. The New York University reactor building was broken into in 1972, and the Oconee reactor's fresh-fuel storage building in 1973. The fence of the Erwin (Tennessee) plant handling highly enriched uranium was partly climbed in 1974 and fully penetrated in 1975, both times without theft [Smith 1978:Encl. 2:App. J#18,29]; likewise at the Kerr McGee plutonium plant in Oklahoma in 1975. In 1975 at the Biblis reactor in Germany, then the world's largest, an MP carried a bazooka into the plant under his coat and presented it to the director; a Canadian Member of Parliament likewise carried an unchecked satchel into the Pickering plant. In 1977, an NRC inspector was admitted to the Fort St. Vrain control room unescorted and without having to identify himself [Subcommittee on Energy & the Environment 1979:46]; similar breaches have occurred at other reactors. In 1976, an unstable former employee drove onto the Three Mile Island site, scaled a security fence, entered a protected area next to the Unit 1 reactor building, and later drove off the site without being apprehended [NRC 1976]. In December 1980, a former employee used a long-out-of-date security pass to enter the Savannah River plutonium production plant, where he stole a truck and other equipment from a high-security area. In 1976 more than a ton of lead shielding was reported stolen from Lawrence Livermore Laboratory, a U.S. bomb design center [DeNike 1975]. In 1974 several tons of unclassified metal were stolen from the nuclear submarine refitting docks at Rosyth, Scotland, apparently through a conspiracy of dockyard employees. (Nuclear submarine fuel, available at the same docks, is highly enriched uranium, the most easily usable bomb material.) [Times 1974a; Hansard 1974] On 5 April 1970, a classified AEC shipment, not fissionable or radioactive, was stolen in an armed REA robbery at Newark Airport [Smith 1978:Encl.3:2]. On 14 October 1970, "an AEC courier guarding a truck shipment of nuclear weapons components" was held up and robbed by three armed persons who took his revolver, wallet, walkie-talkie, submachine gun, and keys to the truck, but did not open or take the truck itself [id.:3]. In the fall of 1978, the FBI arrested two men for conspiring to steal and sell to the Mafia a berthed nuclear submarine in Connecticut, but prosecutors concluded they only meant to abscond with the down payment [Bass et al. 1980:15].

- Nuclear thefts. In 1978, a ship carrying 200 tons of natural uranium

was hijacked, allegedly to Israel [id.:75], breaching EURATOM safeguards, but the governments concerned kept it a secret for nearly ten years. In 1974, a uranium-smuggling operation in India to China or Pakistan via Nepal was exposed [Times 1974]. There have been numerous natural-uranium-related crimes, some involving thefts of ton quantities [Smith 1978:Encl.2:Att.A #4; Bass et al. 1980:14-15]. In 1979, an employee at the GE Fuel Processing Plant in Wilmington, N.C. stole two 30-kg drums of low-enriched uranium, apparently by loading them into the trunk of his car, and used them to try to extort \$100,000 from the management on pain of public embarrassment [Subcommittee on Energy & the Environment 1977:4-5; Bass et al. 1980:15]. Over a period of several years, twenty truckloads of radioactively contaminated tools and scrap metal were illicitly dug up and sold from a waste dump in Beatty, Nevada [NRC 1976a]. "Vast quantities of cannabis resin were smuggled into Britain in radioactive waste drums destined for the Atomic Energy Research Establishment at Harwell," then recovered by asking to have them back for the Pakistani Customs [Times 1975]. There is widespread official suspicion that at least a dozen bombs' worth of highly enriched uranium^(HEU) were stolen by insiders from the NUMEC plant in Apollo, Pennsylvania during the mid-1960s [Fialka 1979; Burnham 1979]. Some observers suspect thefts of HEU at the Erwin, Tennessee plant too, where shortages of material have persisted for many years. Minor amounts of bomb materials--not enough to make a bomb, but enough for materials research or validating a threat --have been stolen from plants in North America (including one 177-g HEU fresh fuel rod from Chalk River in Canada) on at least three acknowledged occasions [NRC 1979; Smith 1978:Encl.2:App.J #47, cov. ltr. 2], not counting mere inventory discrepancies. A substrategic shipment of HEU to Romania arrived with its seals tampered with, and the IAEA did not confirm it was all there for "a couple of weeks" [Subcommittee on Energy & the Environment 1977:3-7].

- Miscellaneous human and institutional flaws. "In October 1974, Italian government officials announced that they had discovered a plot by right-wing terrorists to poison Italy's aqueducts with radioactive waste material stolen from a nuclear research center in Northern Italy. The alleged threat was associated with revelations of a planned assassination and political coup by right-wing elements. An engineer at the research center was named as a conspirator [and a senior general and the former head of the Secret Service were arrested], but the allegations were never substantiated. The case became entangled in legal technicalities. Whether the alleged plot, which gained widespread publicity in Italy, was real or not has never been determined." [de Leon et al. 1978:30] An analytic laboratory used by the Japanese nuclear industry to monitor effluents was shut down by the government for falsifying

and fabricating test results [Nuclear Engineering International 1974a]; in April 1981, a 40-day coverup of improper effluent discharges was revealed at Japan's Tsuruga reactor. Commonwealth Edison Co. (the most nuclearized U.S. utility) and two of its officials were indicted on charges of conspiracy to falsify records "by omitting the fact that protective doors leading to the vital area of the [Quad Cities] plant had been found unlocked and unguarded" [New York Times 1980c].

- Malicious use of nuclear materials. Though many radioactive sources and medical radioisotopes have been stolen [Finley et al. 1980:App.I; AP 1974; Nuclear News 1974; Los Angeles Times 1974,1974a; de Leon et al. 1978:30], and some shipments of strategic materials have been misrouted, mislaid, or even dropped off trucks [Finley et al. 1980:H-4], only three instances of malicious use are known so far: a Squibb radiopharmaceuticals worker put ^{131}I in another's drink (causing a 3.8- μCi thyroid uptake) [E.R. Squibb & Sons, Inc. 1971]; a hated supervisor at the Cap de la Hague reprocessing plant was exposed during six months to about 10-15 R/h of hard gamma radiation from stolen wastes secreted under the seat of his car by a worker [Daily Mail 1979a; Not Man Apart 1981]; and in April 1974 the interior of some train coaches in Vienna was sprinkled with substantial but nonlethal amounts of ^{131}I [de Leon et al. 1978:30], contaminating at least twelve passengers. There have been reports [Bass et al. 1980:77] of the use in Europe of nuclear materials in an attempted suicide, and that a thief who tampered with a stolen radioactive source may well have been killed by it [AP 1974]. A Tulsa radiographer died of radiation apparently received from a stolen ^{192}Ir source [New York Times 1981a].

3.4.2. Nuclear terrorism: resources.

The foregoing history of actual incidents of nuclear terrorism, sabotage, theft, and related institutional failures shows an increasing involvement by international terrorist groups, and a considerable scope for more. It is therefore important to examine what sorts of resources such a group can bring to bear on nuclear facilities. These resources help to determine the achievable level of damage. In the substantial literature of nuclear threat assessment [e.g. Wagner 1977], most of the studies commonly quoted to reassure the public that nuclear plants are very resistant to sabotage expressly exclude the possibility of "military action and damage by foreign agents or subversive organizations" [e.g. Turner et al. 1970]; that is, they consider, in practical effect, only lone disgruntled employees and the like. But international groups have far greater resources, and some can even call on the resources of wealthy governments, which in turn may find such a connection useful for their own ends. "Finding modern conventional war inefficient, uneconomical, and ineffec-

tive, some nations may be drawn to exploit the demonstrated possibilities and greater potential of terrorism, and employ terrorist groups or tactics in surrogate warfare against other nations. This requires an investment far smaller than the cost of a conventional war; it debilitates the enemy; and it is deniable." [RAND 1980:12] Who are these possible surrogates and what are their strengths and resources?

There are estimated to be about fifty terrorist organizations in the world, with a total of about three thousand active members, perhaps an equal number of peripheral supporters, and about two hundred members constituting the "primary transnational threat" [Kupperman & Trent 1979:5]. Several groups sometimes participate jointly in an action. This makes it difficult to determine how many terrorists might be expected to join in a single attack on a particular nuclear facility. In the U.S., where the nuclear regulatory philosophy encourages formulation of specific threat levels which licensees are to guard against, there is a long-running debate over this number, and it has risen steadily during the past ten years. At first it was thought to be "several," meaning three, of whom one could be an insider, and there was a consensus that security systems were not adequate for this threat [Eschwege 1974:2; Subcommittee on Energy & the Environment 1977:204]. Upgraded security measures were then again outrun by a heightened threat estimate of a "small group" (six) aided by up to two insiders. More recently, after several official studies, a consensus has emerged that "fifteen highly trained men, no more than three of [whom]...work within the facility..., [the insiders to include] anyone up to the higher levels of management," is a reasonable threat level [Rosenbaum et al. 1974:S6623; Cochran 1977]. But this debate is reminiscent of medieval theologians' disputations, since the history of criminal and terrorist enterprises clearly shows that attackers bring with them "as many as they need...to do the job, and no more. The fact that most came with a handful of persons, 3 to 6, thus does not represent an upper limit on their capacity" but only their estimate of what would be "necessary to accomplish their mission" [Office of Technology Assessment 1977a:197]. More stringent security precautions would simply elicit a stronger attack without obvious limit.

Another warning against underestimating attackers comes from a review [de Leon et al. 1978:42] of past commando raids. Most "were carried out against protected targets at least as well armed as the commandos, conditions that would hardly seem to bode well for the raiders. Yet, with the advantages of greater flexibility and tactical surprise, the raids succeeded three-fourths of the time and against some targets whose defenses could have prevailed against much larger forces: if one excludes those failures that were not due to enemy

action, the ~~commandos~~ were successful almost 90 percent of the time. This rate of success speaks highly for the professional skill and ingenuity of the raiders, and particularly for their use of surprise. (It also bodes ill for the use of mathematical engagement models [or security plans] in which force ratios determine the outcome.)"

The success of such raids depends on accurate intelligence and precise planning--especially in such operations as Palmach's destruction of eleven bridges in one night, or raids in which British and Israeli commandos seized and carried off German and Egyptian radar bases respectively [*id.*:19]. Similar attributes determined the success of task-force crimes. "In the 45 cases reviewed, criminals were able to assemble teams of as many as twenty people (yet remain undiscovered), breach thick walls and vaults and neutralize modern alarm systems, and devote up to 2 years of planning for a single 'caper.'" [*id.*: vi]. Considerable technical sophistication has also been displayed [*id.*: 12; Burnham 1975:57-59]. "In 1970, an electronics expert connected with organized crime was detected in what appeared to be an elaborate method of monitoring the activities of the Chicago police. He was cruising near the Chicago Police Department's lake front headquarters in a converted mine-sweeper laden with radio-intercept equipment." [*id.*:59]. It is commonly asserted that no group as large as, say, a dozen people could be assembled and trained for a nuclear plant attack without coming to the authorities' attention; but larger groups in past criminal efforts have escaped both notice beforehand and capture afterwards. Indeed, 13 mercenaries training with automatic weapons for jungle warfare were arrested for trespass after five days' secret maneuvers on the borders of the Crystal River nuclear power plant in Florida [Prugh 1981]. They were observed more or less by accident, and nobody knew who they were--whether they were "a drug-offloading operation, a subversive group trying to get the power plant or a CIA operation," according to the sheriff. His aide added: "If they were the real McCoy, we wouldn't have been any match for 'em....This damn sure oughta wake up the nuclear power industry....A good assault team could have taken that plant." [*id.*] The month after the 13 mercenaries were released on their own recognizance, two of them were rearrested with guns and explosives in Miami, where it was believed they were about to plant a bomb [*Los Angeles Times* 1981h].

Such a straightforward light-infantry group is a less formidable threat, however, than just one or two insiders with knowledge of and access to the plant's vital areas. Insider aid has characterized many of the biggest and smoothest thefts and hijackings [de Leon *et al.* 1978:13f; Bass *et al.* 1980:17]. (Impersonation of insiders has also worked every time it was tried [de Leon *et*

al. 1978:14].) "In the \$5.8 million theft from Lufthansa at the JFK Airport, a ten-year Lufthansa employee was promised \$300,000 (more than any other participant)...[simply to leave] his post for more than an hour and a half." [Bass et al. 1980:17] A Bank of New Mexico burglary on the Sandia nuclear base in 1955 appears to have had inside help on the base [de Leon et al. 1978:13], and other examples cited above indicate that even nuclear facilities requiring the most stringent clearance and vetting of employees may harbor potential criminals. The former security director of the Atomic Energy Commission was himself sentenced to three years' probation in 1973 after borrowing \$239,000 from fellow AEC employees, spending much of it at the racetrack, and failing to repay over \$170,000 [Satchell 1973].

A particularly worrisome sort of insider help is security guards. As of 1977 [Comptroller General of the U.S. 1977:8], guard forces at many reactors not only were of low quality, but had a turnover rate of a third to a half per year, with departing guards taking with them an intimate knowledge of up-to-date security arrangements. A local newspaper reporter got a job as a security guard at Three Mile Island, then prepared a series of articles which the utility unsuccessfully sought an injunction to suppress on the grounds that revealing "the specific details of the security system...presents a significant, serious, grave security threat....[T]here is a threat to the health of the public, and national security is involved if someone gets in there to hold the plant hostage for whatever reason." [New York Times 1980b]

A U.S. Marshals Service review of reactor guard forces in 1975 [Comptroller General of the U.S. 1977:9] found they had weak allegiance, high turnover rate, poor background checks and supervision, inferior equipment, weak legal authority, poor rapport with local police, poor mobility, no uniform physical-fitness standards, low public confidence, and little training. Many of these weaknesses persist today. Background checks have been a particularly sore point since a convicted and paroled armed robber got a job as a security guard under an alias at the former Kerr McGee plutonium fuel fabrication plant in Oklahoma; he was found out and fired in 1974, then six months later arrested in connection with an attempted bank robbery in which a woman was shot [Smith 1978:Encl.2:App.J#8]. Even with honest guards, breaches of security are fairly common. A woman working at Browns Ferry forgot she had a pistol in her purse and carried it through a guardpost undetected in February 1980 [Emshwiller 1980a:13]; GAO auditors in 1977 "were able to pick the locks and open several doors to vital areas of [a nuclear power] plant by using a screwdriver or a piece of wire...found on the ground near the door" [Comptroller General of the

U.S. 1977:15]; and other breaches too numerous to mention have elicited NRC fines of utilities on almost a monthly basis.

Except at the eleven federal facilities handling bomb material, where new protective devices include armored cars with light machine guns, U.S. nuclear plants are defended by small numbers of guards with conventional light arms. These are clearly no match for the sort of firepower that even a handful of terrorists could deploy against a nuclear (or any other sort of energy) facility. These potential weapons include the following main categories:

- Firearms: past terrorist and criminal attacks have used all available civilian and military firearms up to and including heavy machine guns, 20mm cannons, antitank guns, and recoilless rifles. Modern counterinsurgency arms now available to terrorists include [Jenkins 1975a:14] "tiny--some less than 15 inches long--silent submachine guns." Automatic weapons are readily available [Burnham 1975:69]. "Enough weapons and ammunition to outfit 10 combat battalions numbering 8000 men were stolen from U.S. military installations around the world between 1971 and 1974" [Aspin 1975].

- Mortars--especially well suited for attacks on spent fuel pools, switchyards, and other facilities unprotected from above. A single North Vietnamese mortar team caused about \$5 billion damage to the U.S. airbase at Pleiku. "A Belgian arms manufacturing firm has...developed a disposable, lightweight, silent mortar which can be used against personnel and also fires a projectile with a spherical warhead designed to produce a 'shattering effect' suitable for the 'destruction of utilities, communications, and light structures.' The full field unit, which weighs only 22 pounds, includes the firing tube plus seven rounds. All seven rounds can be put in the air before the first round hits." [Jenkins 1975a:14]

- Bazookas and similar unguided rockets. Aspin [1975] notes that "In August 1974, ninety anti-tank weapons were stolen by a Yugoslav national who was an employee of the U.S. Army in Germany." These were recaptured, but many more were stolen and later turned up in the hands of criminals and terrorists. Their shaped-charge warheads are specifically designed to penetrate thick armor. World War II-vintage bazookas have a range of nearly 400 m. Their contemporary version, the U.S. Light Antitank Weapon (LAW), is a five-pound rocket effective at 300 m against stationary targets, and shoulder-fired from a disposable tube [Kupperman & Trent 1979:56]. One was unsuccessfully fired at a West Coast police station in 1974; many have been stolen [Burnham 1975:69]. The similar Soviet RPG-7 was used in the Orly Airport attack in January 1975. Both, and counterparts such as the French Strim F-1, are portable, suitcase-sized, and easy to conceal or disguise. "[T]here has not been a recent Soviet-influ-

enced conflict in which the recipients of Russia's support were not carrying RPG-7s" [Kupperman & Trent 1979:83]. Still deadlier versions are now under development, with ranges "far greater" than 300 m [id.:56].

- Light, precision-guided rockets designed for shoulder-firing against aircraft (like the Soviet SA-7 or "Strela" and the U.S. "Redeye", both of which have terminal infrared guidance and a range of several km). Redeye weighs under 30 pounds and is about four feet long; its successor, "Stinger," is no bigger but is faster, longer-range, and more accurate [Jenkins 1975a:13]. The British "Blowpipe" is radio-guided by its aimer; the supersonic, tripod-mounted Swedish RB-70 has laser guidance, "weighs under 180 pounds, breaks down into three smaller packages, and can be operated by one man with minimal training". These latter two missiles can shoot down aircraft approaching head-on [id.]. Palestinian terrorists have Strela rockets and were arrested with some near the Rome Airport in September 1973 and at the edge of the Nairobi airport in January 1976 [Kupperman & Trent 1979:30-31]. A Strela may have been used to shoot down two Rhodesian passenger planes in the past three years. It could be used both for standoff attacks on stationary facilities and to shoot down incoming airborne security forces.

- Analogous precision-guided munitions (PGMs) designed for antitank use. The U.S. "Dragon" and TOW rockets and the Soviet "Sagger" are wire-guided, use laser target acquisition, have ranges of several km, weigh generally under 30 pounds, and can be carried and operated by one person. The French/German "Milan," somewhat smaller and with semiautomatic guidance, is even more portable and is being deployed by the tens of thousands [Jenkins 1975a:14]. The Dragon, TOW, and Sagger shaped-charge warheads "can pierce several feet of homogeneous armor plate" [Kupperman & Trent 1979:55]. They are more commonly available than their anti-aircraft counterparts. It would not be surprising if at least hundreds of them were in terrorists' hands today. They are ideal for standoff attacks against even semihardened nuclear facilities, as well as for attacking any vehicles in which security forces would be likely to arrive.

- Specialized rockets and grenades. The German-designed antitank "Armbrust 300," designed for urban warfare, "has no backblast, making it possible to fire the weapon from inside a room--something no rocket launcher can do now. The Germans expect to produce the 'Armbrust' in large quantities." [Jenkins 1975a:14] A new projectile that can be fired from the U.S. M-79 grenade launcher (many of which have reportedly been stolen) "is capable of penetrating two inches of armor plate and igniting any fuel behind it." [id.]

- Poison gas. In April 1975, terrorists stole three liters of mustard gas from German Army bunkers; several cities, including Stuttgart and Bonn, were

threatened with a gas attack [Guardian 1975a]. The "Alphabet Bomber" threatened in 1974 to "destroy the entire personnel of Capitol Hill" with two tons of sarin nerve gas, and had in fact assembled all but one of the ingredients needed to make it [Bass et al. 1980:25-26]. A letter bomb containing a vial of nerve gas has reportedly been intercepted in the United States [Evening Standard 1976]. Viennese police in 1975 arrested German entrepreneurs for conspiring to sell tabun nerve gas in the Middle East [Kupperman & Trent 1979:5]; they had already made a liter of it--a mere whiff of which would cause unconsciousness in five seconds and death within five minutes--and packed it into bottles, capsules, and spray cans [Evening Standard 1976; Ottawa Citizen 1976]. Methods of making such substances have been published, and some highly toxic nerve-gas analogues are commercially available in bulk as organophosphorus insecticides. An inhaled lethal dose of sarin nerve gas to a normally respiring 70-kg person is about 1 mg. VX nerve gas, whose method of preparation has also been printed, is ten times this toxic by inhalation and 300 times as toxic by contact [Kupperman & Trent 1979:65], and can be made by a "moderately competent organic chemist, with limited laboratory facilities" and willingness to take risks [id.]. Nonlethal incapacitating gases like Mace® are also widely available.

- Explosives, including breaching, shaped, platter, airblast, and fuel-air detonation charges. These are readily available at a wide range of sophistication, ranging from disguisable plastic explosives and specialized cutting and penetration jets to the crude 770-kg truckload of fertilizer/fuel-oil explosive which destroyed the Army Mathematics Research Center at the University of Wisconsin in 1970 [Pike 1972]. (Such a charge at 10 m produces overpressures of order 150 psi, six times the level severely damaging reinforced concrete.) Many tons of commercial explosives are stolen every year [Burnham 1975:50]. Nuclear explosives offer special capabilities that will be considered below.

- Aircraft. The same group that caused one death and \$6 million in damage with the ANFO truck bomb at the University of Wisconsin had also tried to sabotage a power station supplying a munitions plant, and had made an unsuccessful aerial attack in a stolen airplane against the same munitions plant [Burnham 1975:49]. Fixed-wing aircraft have been used in several bombing attempts, particularly in Northern Ireland. Helicopters have been used in jailbreaks in the U.S. [de Leon et al. 1978:35] and in Mexico and Eire, and by Pfc. Robert K. Preston in his 17 February 1974 landing on the White House lawn. Palestinian terrorists have recently used even a hot-air balloon to enter Lebanon, and of course Nazi commandos often used gliders with great success. Commercial and, on occasion, even military aircraft are hijacked throughout the world, and could be used for access, weapon delivery, or kamikaze attack.

- Ships, small submersible vessels, and frogmen are undoubtedly available to terrorists. Ships carrying torpedoes, depth charges, and guided rockets may be available. Portable missiles can be fired even from a rowboat.

- Tanks and similar vehicles are sufficiently available at National Guard and Army bases, where a wide variety of other sizable weapons have been stolen in the past, that it is not unrealistic to contemplate their hijacking. Some incidents of this kind have already occurred. Just heavy construction equipment, which is commonly available to civilians, lends itself to adaptation, and could readily be armored to withstand the light-infantry arms issued to guards. In Louisiana in June 1967, a large construction crane was driven into three large transmission-line towers to destroy them [McCullough et al. 1968].

3.4.3. Sabotage of nuclear facilities.

With such firepower at their command, what technical vulnerabilities might enable terrorists (or acts of war) to achieve major releases of radioactivity from nuclear facilities?

The first thing to be understood about those facilities is that their radioactive inventories are very large. The magnitudes involved--and the diligent attention needed to prevent their accidental release--can be illustrated by a few simple examples. At equilibrium, a 1-GWe LWR contains over 15 GCi* of radioactivity, including about 12.5 GCi of fission products and 3.1 GCi of persistent transuranic elements such as plutonium. Among the more important fission products is 72 MCi* of volatile iodine-131 (^{131}I), a thyroid-seeker with a half-life of about a week. (This means that half of its remaining radioactivity decays weekly, so that after ten half-lives it is reduced to 1/1024th of its original potency; after twenty half-lives, to just under a millionth; and so on.) Holdren [1974] points out that a quarter of that ^{131}I inventory would suffice to contaminate the atmosphere over the 48 coterminous States to an altitude of 10 km to twice the maximum permissible concentration (MPC) for that isotope. Half of the 5.2-MCi inventory of the important bone-seeking fission product strontium-90 (^{90}Sr), which has a 28-year half-life, would suffice to contaminate the same area's annual freshwater runoff to six times the MPC. Such estimates are used not to suggest that such widespread, uniform dispersion would actually occur, but to stress the exquisite care that containment of such large inventories demands.

Another calculation [Morrison et al. 1971] assumes that, in accordance with the "design basis accident," all the radioiodine in a 1-GWe LWR is vola-

*One curie (Ci) undergoes 37 billion disintegrations per second--the activity of a gram of radium. One GCi (billion Ci) or MCi (million Ci) is a huge unit.

tilized and half of it enters the containment dome. If that containment then fails or is deliberately breached, then half of its radioiodine inventory (a quarter that in the core), held up for a day (4.6-fold decay), will produce under moderately stable meteorological conditions a cloud-centerline dose of 300 rem to an adult thyroid at a downwind range of 200 km. Such a dose, while not acutely dangerous (as a 300-rem whole-body dose would be), is certainly more than would be considered tolerable. Before placing too much faith in the containment, it is worth noting that the integrated decay heat from the core would suffice to melt down through an iron cylinder 3.3 m in diameter and over 210 m high [*id.*]--to say nothing of possible steam or hydrogen explosions or other effects involving thermal shock, carbon dioxide pressure from decomposing concrete, etc. This decay heat, arising from radioactive decay in the core, cannot be turned off, reduced, or controlled in any way, and must be safely removed somehow--a key distinction between nuclear heat and heat from chemical combustion.

This decay heat--initially about 6-10% of the reactor's full-power heat output, thus amounting to hundreds of megawatts for a modern power reactor--is only one of its several sources of internal energy which, properly harnessed, can help a saboteur to release much of the core's radioactivity, even if the reactor has already been shut down. Another is the potential for chemical reactions (such as Zircaloy/water or hydrogen/oxygen). Yet another is the pressures and momenta of internal fluids: in a big PWR, the mechanical energy of circulating hot water is equivalent to about 0.025 kT, and its thermal energy, to several kT. Much of the reactor's complexity arises from multiple protective devices which are supposed to prevent a major release; but these all have their vulnerabilities.

Among these is their need for electric power. Without electricity, most of the shutdown, cooling, and control devices cannot work. Few have adequate battery storage; instead, they rely on offsite power from the grid, onsite power from the station's own switchyard, or emergency diesel generators (which are not very reliable). The Rasmussen Report's fault and event trees [NRC 1975] reveal that common-mode electrical failure causes severe and unstoppable meltdowns in which most mitigating devices do not work. Low-technology sabotage could disable diesel generators in between their periodic tests, then at leisure, before they are fixed, cut offsite power. One person without special skills could do both, either by access to the site or (in most cases) by stand-off attack, as the diesels are often badly protected and sometimes housed in light external sheds. Operating power reactors have already experienced failure of all backup power (fortunately not simultaneous with a grid outage)

[Pollard 1979:42] and had grid instability resulting in reactor shutdown and area blackouts [id.:46].

More complex modes of attack can be designed with the aid of the Rasmussen Report and detailed design information publicly available [Subcommittee on Energy & the Env't. 1977:215]. They can either mimic hypothetical accident sequences, as most analyses assume is necessary, or simplify and shortcut them. Two promising approaches are producing a rapid power excursion, beyond the reactor's ability to cool the fuel (a worrisome class of potential accidents, especially in BWRs), and "interrupting the supply of cooling to a shutdown reactor" [id.:14] so that its decay heat--initially many kWt per liter of core--melts the fuel. These can be done from either onsite or offsite, the latter referring to remote targets or to use of standoff weapons against the plant itself. Remote targets include transmission lines, related switchyards and transformers not onsite, and any cooling-water intake necessary to provide an ultimate heat sink to the plant: for any power plant, but especially for nuclear plants because they need cooling for decay heat after shutdown, "the screenhouse [intake structure] is probably the most vulnerable point for sabotage in steam generating stations." [Bisset 1958] (This may also be one of the things Dr. Bruce Welch, a former Navy Underwater Demolitions officer, had in mind in his widely publicized Joint Committee on Atomic Energy testimony, 28 March 1974, that with a few randomly selected military demolition people he "could sabotage virtually any nuclear reactor in the country." A retired Green Beret colonel, Aaron Bank, gave unpublished JCAE testimony to similar effect about San Onofre, whose intake structures are unusually accessible.) Standoff weapons, besides conventional ones such as mortars, rockets, precision-guided munitions, fixed-wing and helicopter aircraft, etc., may include remotely piloted aircraft (the remote-control apparatus now widely available to hobbyists is probably adaptable to operating standard light aircraft). Inspection of seismic resonance analyses of major reactor structures also suggests that an exotic possibility--standoff attack by infrasound generators tuned to published resonant frequencies--cannot be wholly disregarded; and of course key control and safety circuitry, as noted on p.96, may be vulnerable to electromagnetic pulses, fair facsimiles of which can be generated with homemade standoff devices.

Onsite overt attacks could be meant to take over the plant. The staff could be subdued or killed with ordinary weapons or by introducing a rapidly lethal gas into the ventilating system. The latter method might be quick enough to prevent operators from raising the alarm, isolating control-room ventilation, or shutting down the reactor, and it might be the method of choice for an insider. (It also raises the question, nowhere answered in the

literature, of how safe a power reactor would remain if all its staff suddenly dropped dead.) Once the plant had been seized, its security devices and the shielding and life-support systems of the control room would all help to protect its occupiers from both invaders and external radioactive releases. The occupants could then do either of two things, or both in succession, at comparative leisure.

First, they could use their power over the costly plant and its dangerous contents as a basis for political negotiations. These might be secret initially, with the threat of disclosure and ensuing public panic used as a bargaining chip. Various concessions could be demanded. In their absence--or possibly straightaway if the occupiers are of the type that prefer people dead to people watching, or cannot competently maintain the plant in safe condition--serious damage could be undertaken, leading at a minimum to the economic loss of the plant and probable ruin for its owners; at a maximum, to major releases.

Two types of deliberate damage, not mutually exclusive, seem possible. Mere demolition is straightforward. Blowing holes in the crucial containment building is not even necessary, since terrorists can simply open its personnel airlock doors. (Schleimer [1974:27n8] notes that the San Onofre information center showed every hour a film demonstrating how these doors work.) Mindful of the near-miss at Browns Ferry, a low-technology saboteur with an experimental frame of mind might want to see what arson in the cable-spreading room would do. Alternatively, depending on the occupiers' technical knowledge, control systems might be disabled, bypassed, or reversed so as to make the plant destroy itself. Both normal and emergency coolant could be removed or stagnated. In some circumstances, large overpower transients might be achievable, especially with the help of insiders. The occupiers could use, alter, or disable all the electrical systems, controls, cables, valves, pumps, pipes, etc. virtually at will. Even major components are highly vulnerable to commercially available shaped charges, to thermic rods ("burn bars"), and to thermal shock.

Once sabotage had begun, repairs and countermeasures could rapidly become impossible even if the plant's operators quickly regained control of the site. Key parts of the plant could by then already be filled with steam, water, noxious gases, or high levels of radioactivity. It could be impossible even to assess damage. Access to the inside or outside of the plant could readily be interdicted by radioactive releases, chemical poisons, or conventional munitions wielded by defenders from their concrete fortress--which their adversaries would hardly want to damage. Those adversaries would have to include and coordinate counterinsurgency forces, health-physics teams, and reactor engineers. Further, though one can doubtless assume considerable ingenuity and

courage on the part of the forces of law and order, the history of major nuclear accidents suggests that one can also expect a full measure of confusion, error, foolishness, and possibly panic. Panic would almost certainly ensue in downwind areas, probably leading to considerable loss of life and property and hindering the arrival of backup teams. And of course if a meltdown did occur, then events onsite and releases offsite would, by general consensus, be uncontrollable and unstoppable in principle, owing to extreme radiation fields and the formidable temperatures, masses, and chemical properties of the materials involved. Major psychological, political, and economic trauma on a national or world scale would be inevitable. Civil liberties and indeed civil (as opposed to martial) law would probably, as in a nuclear bomb threat, be among the early casualties [Blair & Brewer 1977].

Any consideration of potential releases of radioactive material by sabotage or war must look at the whole nuclear fuel cycle, not just reactors. One modest but ubiquitous source, passing through the midst of our largest cities, is casks carrying spent reactor fuel. A single 3-element shipment, after 150 days' cooling, still contains several megacuries [Finley *et al.* 1980:103], including 0.52 MCi of radiocesium ($^{134},^{137}\text{Cs}$)--a biologically active nuclide slightly longer-lived than strontium-90 and even more important from the standpoint of land contamination, since, unlike strontium-90, it emits penetrating hard gamma rays. A highly unlikely accidental dispersal of a much smaller spent-fuel shipment, totalling only 0.2 MCi, in New York City is calculated [*id.*:65-66] to cause \$2 billion in land denial by contamination. (This is not a worst case. Dispersal of 10 kg of plutonium oxide, of which only 5% is assumed to become airborne, causes the same contamination damage plus over 2000 deaths. Dispersal of a 144-Ci polonium-210 source causes scores of deaths and \$9 billion in contamination. All these are shipped through cities too.)

A far larger source term is the inventory of spent fuel in storage pools, currently at reactors but perhaps in the future also at Away-From-Reactor (AFR) centralized pools [Dinneen *et al.* 1980]. Pools at reactors are often badly protected; many are above grade; and the fuel, especially in its first few months of storage, may require active cooling to keep it from melting. And an even more concentrated source of long-lived contaminants, notably ^{90}Sr and ^{137}Cs , is tanks containing high-level reprocessing wastes--the source of two-thirds of the release hazard calculated by Chester & Chester [1976:337]. Such tanks are essential at reprocessing plants for cooling before any solidification of high-level wastes, and are currently holding large inventories at several U.S. sites (West Valley NY, Hanford WA, Savannah River GA, and Idaho Falls ID). The inventories of long-lived isotopes at several sites are in the

GCi (billions of curies) range--enough, if a substantial fraction is dispersed, make a subcontinental area uninhabitable for several centuries. A Barnwell-sized (1500 T/y, or about 50-reactor) reprocessing plant, after five years' operation, stores nearly 5 GCi of the especially hazardous nuclides zirconium-95, niobium-95, ruthenium-103 and -106, and cesium-134 and -137, plus 0.8 GCi of strontium-90. Simple plume calculations suggest that a 1% release from this inventory with rainout from the plume could contaminate tens of thousands of square miles with persistent radiation of tens of rem per year.

To make such a release easier, the reprocessing plant itself, like a reactor, provides substantial internal energies [Gorleben International Review 1979:Ch.3]: large amounts of flammable solvents, ton inventories of fissionable materials that must be carefully protected from accidental criticality, hot reactive acids, thermally and radioactively hot spent fuel and wastes, and such possible accident initiators as a product of solvent radiolysis known as "red oil," which is not well characterized but is empirically known to be an easily detonated high explosive. It is also noteworthy that such a plant separates annually in pure, readily handled form of the order of 10-15 tons, thousands of bombs' worth, of plutonium; in five years the plant separates more fissile material than is present in the entire U.S. nuclear arsenal, accountable with a precision unlikely to be much better than 1%. A saboteur with access to plutonium-dioxide loading or storage areas could assemble in a few minutes, using other materials already present in the plant, a crude nuclear bomb with a yield of order 0.01-0.5 kT--more than sufficient to disperse virtually the whole plutonium inventory and probably a good deal of the fission-product inventory too. (No reprocessing-plant security plan envisages this method.)

Accidents at the Savannah River reprocessing plant have already released 153 Ci of radioiodine (about ten times the Three Mile Island release) in five days [Marter 1963] and 479 kCi of tritium in one day [South Carolina Department of Health & Environmental Control 1974], but these releases, however significant [Alvarez 1980], are trivial compared with what even a modestly serious accident could do [Gorleben International Review 1979; Hatzfeldt *et al.* 1979: 78-98]. Such an accident may have been narrowly averted at the Capde la Hague reprocessing plant in France on 15 April 1980 when a supposedly impossible total electrical failure briefly disabled vital cooling and safety equipment. The potential was also obliquely illustrated by two U.S. accidents in plutonium-handling plants. In the first, Gulf United Nuclear's Plutonium Facility, a mixed-oxide fuel fabrication plant at West Pawling, New York, suffered on 21 December 1972 a fire and two explosions of unspecified origin; these scattered an undetermined amount of plutonium around the facility, which was then perma-

nently closed [Cochran & Speth 1974:10-17]. In the second, the Rocky Flats plutonium weapon-component plant 15 miles from Denver suffered on 11 May 1969 a fire that appears to have been the costliest industrial accident in U.S. history. General Giller, then USAEC Director of Military Applications, testified in subcommittee hearings [Committee on Appropriations 1970] that the fire was "a near catastrophe" and that "hundreds of square miles" could have been contaminated if the fire had burned through the roof. "If the fire had been a little bigger," he said, "it is questionable whether it could have been contained."

These incidents raise the disturbing question--generic to nuclear plants--of "loss-of-supervision" scenarios [Gorleben International Review 1979:Ch.3] whereby a serious release sufficiently contaminates the plant and its environs that it can no longer be properly maintained to fix the damage or even to prevent further deterioration. Experience at the Seveso chemical plant in Italy suggests this is far from idle speculation. It was not far from happening when the Browns Ferry control room filled with acrid smoke in 1975 [Corney 1975], or when a storage tank two miles from the Fort Calhoun, Nebraska nuclear plant spilled 150 tons of anhydrous ammonia in November 1970, forming a 35-foot-thick layer of ammonia that covered some 1000 acres [Pollard 1979:26] (nuclear plants do not always have enough breathing apparatus for everyone). Chester [1976] says that sabotage of the cooling system on a high-level waste tank would lead to boiloff of the water and release of fission products, but this "would take weeks or months, allowing ample time for detection and repair." What if the sabotage has already released so much that nobody can do the repairs? [Gorleben International Review 1979:Ch.3] In 1977, workers at the Windscale reprocessing plant in England went on a 6-week strike, and a cladding fire was feared when they would not allow liquid-nitrogen shipments to cross picket lines. Eventually the [Labour] energy minister had to threaten to call in the Army [AP 1977].

The loss of supervision could be caused by violence, not contamination: as noted above, the operators could be dead or incapacitated. Carl-Friedrich von Weizsäcker recalls a colloquy in which Norman Rasmussen was insisting that the operators would always stay at the plant to keep it safe: they must because the regulations said so. Von Weizsäcker persisted, "What if they don't? What if the reactor is in Beirut, the operators are Christians, and the Syrians are coming?" Whereupon a third person remarked, "I've learned more about reactor safety in the past five minutes than in the previous ten years."

Possible envelopment by an LNG or LPG fireball has already been mentioned as a possible event that could endanger a nuclear facility and disable its operators. Another is airplane crashes. On 25 August 1972, a light plane lost

in dense fog crashed into the Millstone (Connecticut) reactor complex, disabling the 27.6-kV feeder for the transformer operating shutdown systems and cutting off-site telephones for three hours. (The plant did not reduce power.) [Pollard 1979:39] The Big Rock Point reactor in Michigan was apparently such a good landmark that Air Force crews used it for practice bombing runs. On 28 May 1974, the Prairie Island reactor was repeatedly overflown at low altitude by a light plane piloted by a known criminal who appeared to be photographing it; subsequent FBI investigations "did not reveal any malevolent intention or violation of the law." [Smith 1978:Encl.2:App.J #10] On 3 September 1975, an Air Force B-52 carrying no weapons exploded in flight and crashed about 20 miles from the Savannah River reprocessing plant [Washington Post 1975]. On 10 November 1972, three men hijacked a Southern Airways commercial flight to Canada, made the pilot circle over the Oak Ridge complex, threatened to crash the plane into it (reports vary as between the Oak Ridge Research Reactor and the Y-12 plant), collected a reported \$2 million ransom, and landed in Cuba [Burnham 1975:124].

In view of this history, it is disturbing that most plants are designed to withstand a crash only of a fairly small aircraft. Wall [1974], for example, offers an analysis based on a 1968 census of the civil aviation fleet, before widebody jets, and considers the impact only of the engines, not of the airframe. Likewise, the official safety report for the proposed Gorleben reprocessing plant in the Federal Republic of Germany considered only crashes by Phantom jets at 215 m/s, whereas a Boeing 747 at 200 m/s would produce a peak impact nearly six times as big and lasting more than twice as long [Hatzfeldt et al. 1979:92]. By a lucky irony, the double containment strength that enabled the Three Mile Island containment shell to withstand the hydrogen explosion was designed in because a commercial flight lane for low-level approaches to the Harrisburg airport passes essentially over the plant; but it is unlikely that most reactors or other nuclear facilities are really equipped to handle a crash by well-laden widebody aircraft. The tendency of the jet fuel to cause an after-crash fire about half the time would also complicate shutdown and repair efforts in the stricken plant.

Our selection of examples of potential sabotage has been illustrative, not comprehensive. Many other points of vulnerability can be found in the nuclear fuel cycle. For example, heavy-water plants, operating at Savannah River and in Canada, have enormous inventories of hydrogen sulfide, whose toxicity limit is 550 ppm or 750 mg/m³. Some official calculations suggest that a major release of H₂S could be about as hazardous as a modest reactor accident; and the plants have far less protection than a reactor. We have also not

sought here to consider all possible methods of sabotage, even in general terms. Many nuclear facilities, for example, are highly vulnerable to insider reprogramming or disabling of their control computers, resetting of their instrument trip points, biasing of their calibration standards, etc. It is also possible to attack a plant by standoff in time rather than in space. Now that digital watches with long-lived, low-drain batteries are widely available, along with sophisticated and highly reliable electronics of all kinds, it is feasible to conceal a conventional chemical bomb (or at least to say one has done so) in a reactor under construction. One extortionist recently claimed he had put a bomb in a concrete wall being poured at a reactor, and it proved very difficult to find out whether the claim was true. On occasion, foreign objects considerably more obtrusive than a lump inside a concrete wall have escaped detection for a surprising time: on 8 May 1972, for example, Commonwealth Edison reported to the AEC that they had retrieved a complete Heliarc® welding rig, complete with 7.5-m cables and hose, from inside a malfunctioning jet pump. Substantial foreign bodies have even been retrieved from reactor cores. The technical and operational sophistication of the extortionist's bomb that caused \$3 million damage to Harvey's Resort hotel-casino in Stateline, Nevada on 26 August 1980 (giving rise to hundreds of imitative threats over the following year [Los Angeles Times 1981f]) suggests that this sort of threat, skillfully done, could shut down a lot of nuclear capacity virtually at will.

3.4.4. Consequences of major releases.

Having reviewed the kinds of resources and techniques that can be devoted to achieving a major release of radioactivity from nuclear facilities, we must now consider the possible consequences--radiological, social, and economic. Unfortunately, most of the literature on major nuclear accidents may understate the possible results of successful sabotage. According to the General Accounting Office [Comptroller General of the U.S. 1977:6], a classified Sandia assessment of reactor sabotage, for example, found that the consequences could not exceed the maximum calculated in the Rasmussen Report [NRC 1975] for a major accident--3300 prompt deaths, 1500 delayed cancer deaths per year for 10-40 years, and \$14 billion in property damage. Yet the Rasmussen Report did not present those figures as the results of a worst possible accident: worse ones were physically possible but were assigned a low probability and not considered [Kendall et al. 1977:61f]. Further, a saboteur would be free to select all-worst-case conditions--near-urban reactor, mature core, meteorological inversion, wind blowing toward the city--and could disable mitigating

systems (such as containment sprays) and breach the containment. Nonetheless, most commentators have uncritically accepted contentions by the Sandia group (whose supporting analysis, if any, is unavailable to the public), in the Rasmussen Report itself (which provided none--it nowhere considered sabotage), and elsewhere that the consequences of sabotage could not exceed those of a serious accident. That finding has never been justified in open literature and "is very likely untrue" [id.:61]. For lack of better data, however, we shall take the consequences of accidents as indicative of those of successful sabotage; and it is common ground that both could be graver than any peacetime disaster, and perhaps any wartime disaster, in recent world history.

A recent review [Beyea 1980] of the long-distance consequences of major accidental releases from a power reactor--assumed for analytic specificity to be Three Mile Island--finds that delayed effects, especially thyroid damage and land contamination, "can be a concern more than one hundred miles downwind from an accident and for many decades" [:4], i.e. far beyond "the distances for which emergency planning is required by current Federal guidelines" [:2]. Such large releases can arise in accidents only if the containment building fails or is bypassed, but this can occur with or without a full core meltdown, due to isolation failure, overpressurization after containment spray failure, or perhaps a hydrogen explosion [:6]. (The hydrogen explosion during the TMI accident may have been sufficient to breach smaller or weaker containment buildings in use at many other reactors [id.] .) A core meltdown would add the possibility of violent steam explosions, and would release enough hydrogen or carbon dioxide or both to make the probability of containment rupture about 0.2 (according to the Rasmussen Report) for large containments and nearly 1.0 for small ones, such as those on nearly all boiling-water reactors [:6-7]. Dispersion calculations show [:11-13] that depending on wind direction, delayed cancer deaths alone, in the 75 years following the release, beyond 50 miles from the reactor (ignoring all those closer to it), would probably range from about 0 to about 60,000 under typical meteorological conditions, assuming the reactor core was mature, i.e. to be refueled shortly. The beyond-50-miles zone would also suffer a similar number of genetic defects, from 0 to about 450,000 thyroid nodules, and land contamination of from 0 to about 5300 square miles (with short-term farming restrictions on up to 175,000 square miles). Most of this population exposure would be at doses of order tens of rem or less. Prompt deaths, from whole-body exposure over 150 rem, would occur only within a few tens of miles of the reactor. This region, which in some cases (e.g. Indian Point, Zion) includes major cities, is excluded from Beyea's calculations but

considered in such studies as the Rasmussen Report [NRC 1975], whose "maximum" consequences are noted above.

Another recent analysis [Fetter & Tsipis 1980,1981] has compared the radioactive releases that might be caused by a major reactor accident, a nuclear explosion, and the former caused by the latter. The radioactivity from a one-megaton bomb explosion is some 40 TCi (4×10^{13} curies) at detonation, compared with an equilibrium core activity of over 15 GCi--over 2000 times smaller--for a 1-GWe light-water reactor. But the activity of the bomb debris decays far faster, so that after the first hour, the bomb activity is only one and a half orders of magnitude greater than the reactor's; after a day, the same; after a month, an order of magnitude less (i.e. of the same order as a 10% release from the reactor core to the environment); after a year, 10 times less; after five years, 100 times less; after 25 years, 1000 times less [:20-22]. Accordingly, a bomb that vaporizes a reactor core will greatly increase (by tenfold after one year) the amount of interdicted land. Assuming a ceiling dose limit of 2 rem/y to resettlers, the area seriously contaminated for centuries would be hundreds of square miles (a total of about 400,000 square-mile-years), or about forty times that caused by a 1-megaton surface burst. As we shall note below, similar consequences could arise from a bomb "even of relatively small yield, such as a crude terrorist nuclear device" [1980:29]. That could indeed be worse, since lower yield would not carry the debris so high, and the reactor fallout would therefore be sooner and more intense than if spread over a large stratospheric volume by the strong updrafts of a high-yield explosion.

Thus a nuclear-capable terrorist or a "determined or desperate combatant [in Europe] can, by waiting for the proper weather conditions, devastate a substantial fraction of the industrial capacity of an opponent with a single nuclear weapon aimed on a reactor." [1980:29] The activity released would exceed, perhaps by one or two orders of magnitude, the release in a reactor accident. (Beyea [1980:E-4] assumes a maximum release of 50% of core cesium and rubidium, 70% of iodine, 90% of noble gases, 30% of tellurium and antimony, 6% of barium and strontium, 2% of refractory metals, and 0.4% of lanthanides and actinides. He notes, however [:8], that the actual TMI accident released about as much activity from the fuel elements as had been expected in a full meltdown for release of volatile elements alone, such as cesium and iodine. Even a small bomb could cause essentially 100% release of the entire core.)

Holdren [1981] adds an important footnote to Fetter and Tsipis's calculations: if, as Beyea has done, they also consider the long-term, long-range dose commitments, then a reactor accident alone, with no bomb detonation nearby, is

"within a factor of two of the [one-megaton surface-burst] bomb at distances out to 200 km, closing in beyond that distance and delivering higher total doses than the bomb beyond about 900 km." In an even more direct comparison [:3], Beyea's worst-case accident gives a dose commitment of about 120 million person-rem, compared to Rasmussen's 1000 million; whereas OTA [1979:13] implies 10-100 million person-rem for a 1-MT airburst and 250-3000 million person-rem from a 1-MT groundburst. Thus, contrary to the Fetter and Tsipis conclusion [1981], which concentrates on near-term, short-range effects, even a 1-MT groundburst is not necessarily more destructive radiologically than a severe reactor accident. But conversely [Holdren 1981:4], "the possibility of malicious as well as accidental destruction of a reactor core" returns again to "the unfortunate links between nuclear power and expanded access to the raw materials of nuclear weaponry....For the staggering radiological consequences of destruction of a nuclear reactor by a nuclear weapon--the third case considered by Fetter and Tsipis--put the radiologic damage potential of a fair-sized nuclear arsenal into the hands of any nation or terrorist group with a single, 10-kiloton bomb." (As noted below, a smaller yield would also suffice.)

The consequences of a single act of nuclear sabotage can be comparable, then, to those of nuclear war. Remote siting, undergrounding, containment venting filters, evacuation, thyroid blocking, sheltering, air filtration, and other measures meant to mitigate the effects of reactor accidents would be grossly unequal to the task. The Nuclear Regulatory Commission does not seem much interested even in these modest measures [Beyea 1980], and the nuclear industry seems to feel that mitigation methods are unnecessary or embarrassing. (For example, the Senior Vice President of Philadelphia Electric Company testified on 27 May 1980 that "Evacuation plans are just the window dressing and the final back-up plan"; that a 1.7-mile Low Population Zone for evacuation planning around Limerick is "more than adequate"; and that "Emergencies that will require evacuation will not occur." [Kostmayer & Markey 1980]) This lowers still further the threshold for sabotage that can be disastrously effective.

So far we have considered consequences only at a crude level--death, disease, land denial. But at a societal level, psychological impacts may in fact be more important [e.g. Lifton 1967; Del Tredici 1980; Perelman 1979]. Whether reactor sabotage is technically successful or not may be less important than whether people think it may succeed. The psychological impact of a potential release was strikingly confirmed even before Three Mile Island when a War-of-the-Worlds-type radio drama broadcast in Denmark on 13 November 1973 described a supposed 1982 meltdown in the Barsebäck reactor in Sweden (visible across the narrow straits from Copenhagen), allegedly sending an invisible but deadly

plume towards the Danish capital. Residents panicked; some began to evacuate; some thought their loved ones dead; and it took hours of repeated assurances that it was all fictitious before people got the message [Nuclear Engineering International 1974].

Since "large numbers of people in many countries have become acutely concerned" [Ramberg 1978:4; Farhar et al. 1980] about nuclear risks, it is likely that a major nuclear release will lead to irresistible demands for the shutdown of operating nuclear power plants and, perhaps, of military nuclear plants. In view of deep-seated public attitudes and the many ways which a democracy offers for expressing them, this is not a trivial dimension of vulnerability: it means that a sizeable accident may lead to the loss not of one or two GWe but of 50+ GWe now and of any prospect of more later, to say nothing of political fallout in other countries. Conversely, Jenkins [1975:7] notes that public attitudes may be the most important motivation for terrorists to acquire nuclear bombs or attack nuclear plants: "...the primary attraction to terrorists in going nuclear is not that nuclear weapons would enable terrorists to cause mass casualties, but rather that almost any terrorist action associated with the words 'atomic' or 'nuclear' would automatically generate fear in the minds of the public."

The technical and economic impact of the protracted disabling of any part of the nuclear fuel cycle would tend to be heightened by that cycle's intricate interdependence. It entails not just one but many complex operations whose logistical coordination has remained an elusive goal for several decades. One failure or bottleneck can have unexpected side-effects throughout the rest of the system. Just as reactors can become constipated if there is no place to store their spent fuel (a problem that has lately required the hasty "densification" of many storage pools), or if there are not enough special casks in which to ship it elsewhere, so a reprocessing plant can become constipated if spent fuel arrives faster than technical breakdowns allow it to be handled. This is currently the cause of a serious and worsening problem at both the British and French plants for reprocessing fuel from graphite-moderated gas-cooled reactors. The magnesium-alloy cladding of that fuel corrodes in a matter of years when stored (as it normally is) in water. Persistent problems at both reprocessing plants have led to an increasing backlog of rotting fuel in storage pools. This increases operational problems and occupational hazards, leading to still more breakdowns. At Cap de la Hague, this cascading slowdown has diverted much of the capacity meant for handling oxide (LWR) fuel, incidentally so reducing the plutonium output that France must buy British plutonium to fuel the Super-Phénix fast reactor.

Should fuel cycles ever come to depend on reprocessing (as with breeder reactors), about 50 reactors would depend for their fuel on timely deliveries from a single reprocessing plant. At perhaps \$3-8 billion each, such plants would be too costly to back up. (The several fuel-fabrication plants might offer a similar bottleneck.) Such fuel-cycle dependencies clearly create a remarkable vulnerability: a single, otherwise minor reprocessing problem could idle some \$100+ billion worth of breeders.

Although the sheer cost of replacing a major nuclear plant (or even cleaning up its remains) is probably less of an incentive to sabotage it than resulting releases, costs are not negligible. The extraordinary capital intensity of nuclear plants (new ones typically will cost several billion dollars each) does represent a risk to large blocks of invested capital, as Three Mile Island investors have discovered. Few if any utilities in the world have enough financial safety margin to absorb such a risk, and as Three Mile Island has again demonstrated, institutional preparedness for a multi-billion-dollar loss is also woefully inadequate. America's capital structure is already at risk because many utilities are insolvent, and their debt and equity--the largest single block of paper assets in the whole economy--is the basis of many highly leveraged institutions. (How the insolvency arose and what to do about it are explored further in Appendix A.) Utility finance, and hence capital markets generally, are currently so precarious--and likely to remain so for many years--that another major loss could trigger cascading bankruptcies on a wholly unmanageable scale. The potential economic consequences of losing a major nuclear asset thus go well beyond a particular utility or its ratepayers or investors. Further, the financial community already perceives substantial risk associated with utility investments in general and nuclear-power investments in particular [Emshwiller 1980,1981; Hershey 1981; Bupp 1981; O'Donnell 1981; Marshall 1981a; Parisi 1981; Shearson Loeb Rhoades Inc. 1981:4-9]. What long-term prospects for nuclear finance have survived Three Mile Island would certainly not survive a major episode of sabotage anywhere in the world.

3.4.5. The added risk of nuclear bombs.

The foregoing assessment has mentioned only in passing that the risks described could be greatly increased by the direct and indirect consequences of nuclear explosions, even of low yield (kilotons or less). Unfortunately, the nuclear enterprise, both civil and military, increases the likelihood that nuclear bombs will become more widely available. Ignoring for simplicity the complex details which we have elsewhere treated and documented in detail [Lovins & Lovins 1980], this linkage has three main causes:

1. Every form of every fissionable material used in every nuclear fuel cycle can be made, either directly or when treated with apparatus made widely available by nuclear power, into formidable nuclear bombs--at least in the kiloton range. The other resources needed are available to almost any government, to many nongovernmental groups, and to some able individuals. (Appendix B is a technical assessment of expected explosive yields from plutonium as a function of isotopic composition, chemical form, and design sophistication.) Power reactors are themselves a peculiarly convenient type of military production reactor, providing extremely large scale, zero political cost, and almost no marginal economic cost. The barriers supposedly posed by enrichment and reprocessing technology are not insuperable; even the conversion of one fresh LWR fuel bundle into a bomb's worth of plutonium may be possible on a basement scale. There is no "technical fix" to this problem, and no "political fix" short of global dictatorship. There is no prospect of adequate protection from any present or foreseeable means of monitoring, accounting for, physically protecting, and preventing governmental diversion of fissionable materials--provided that fission (or perhaps fusion) technologies are in widespread use. Thus civil denuclearization is a necessary condition for nonproliferation.

2. It is not only fissionable materials that link reactors to bombs. Much of the equipment, knowledge, technical skill, and organizational structure essential for the former is also helpful for the latter. History suggests that this connection can generate its own momentum through the evolution of technical and commercial lobbies. These can become so powerful and self-contained that they become a government unto themselves, evading (as in the 1950s British bomb program) or overturning (as in the French) established political controls.

3. Perhaps the most important link is that nuclear power provides an innocent "cover" beneath which bomb programs can be readily concealed, and an ambiguity which invites latent proliferators to sidle up to the nuclear threshold by degrees.*

*Conversely, in a world without nuclear power, the materials, skills, and equipment needed to make bombs by any known method would no longer be items of commerce; efforts to get them would be more conspicuous; and being caught trying to get them would be politically far costlier to both customer and supplier, because for the first time the intention would be unambiguously military. Thus civil denuclearization is a largely (though not wholly) sufficient condition for nonproliferation. There are also intricate, reciprocal connections between vertical proliferation--the multiplication and refinement of bombs now possessed by governments--and horizontal proliferation to additional parties. Neither of these problems can be consistently formulated or successfully addressed alone. These issues, and the problem of proliferation generally, are beyond the scope of this study, but are treated elsewhere [Lovins & Lovins 1980].

The resources needed to design and build a working nuclear bomb are highly variable. As shown in Appendix B, but to an extent greater than can be fully explained there, the sophistication of design and construction can vary enormously, depending on the ingenuity and resources available. Rule-of-thumb designs capable of being "thrown together" with generous safety margins can be envisaged and might enter terrorist folklore. In general, official assessments tend to assume more sophistication than is actually needed; but NRC's operating assumption [Gossick 1977] is that "a small non-national group of people" could make a crude bomb if they had "the appropriate technical capabilities" and a formula quantity of fissionable material. (That is equivalent to 5 kg of highly enriched uranium-235 (HEU), similarly reactive amounts of medium-enriched ^{235}U , 2 kg of plutonium of any isotopic composition, or 2 kg of ^{233}U . Some other usable materials, such as ^{237}Np , are not subject to safeguards.) The NRC wisely does not give safeguards any credit for the fact that a larger-than-formula quantity would be needed in crude designs, nor for "the difficulty or any extended length of time involved in designing and fabricating" a bomb [id.]. (Taylor [1973:182] points out that even converting uranium or plutonium nitrate to metal--an optional operation--is no more risky or difficult than converting morphine base to heroin, an operation that has been carried on routinely by criminals in the south of France for many years.)

Regardless of one's view about the resources and skills required, however, the plain fact is that any threat of a clandestine bomb which is competently enough framed to be technically credible is automatically credible. This is because the skills and luck of those claiming to have the bomb are unknown, and because they may well have the fissionable material. This in turn is inescapable because the cumulative statistical uncertainty in U.S. inventories of bomb materials--the margin within which neither presence nor absence of the materials in their proper place can be confirmed--is about 20 tons, i.e. thousands of bombs' worth, for HEU alone [O'Toole 1977], plus some more for plutonium and ^{233}U (141 kg for Savannah River plutonium alone [Burnham 1980]). It is steadily increasing. (A similar situation prevails abroad, and bomb materials can be smuggled across national borders as easily as heroin.) Perhaps no bomb material has been stolen; perhaps the Erwin employees who checked each other for theft under an honor system [Subcommittee on Energy & the Environment 1977a:38] were all honorable; perhaps the NRC Office of Nuclear Materials and Safeguards was being alarmist in proposing to revoke the Erwin plant's license [Burnham 1979b]; perhaps it is pure chance that as of January 1978, eight of the previous twelve inventory periods at Erwin had resulted in the limit of error being exceeded [NRC 1978]; perhaps, even though "a knowledgeable insider

could quite easily have made off with" HEU from the Apollo plant in the 1960s [Subcommittee on Energy & the Environment 1979:7], nobody bothered to; perhaps it is purely coincidental that the statistical alarm-bells in U.S. bomb-materials accounting have been ringing at least a third of the time [Marshall 1981b]. But nobody can give an assurance that matters are so satisfactory. Anyone who claims to possess bomb material and seems to know what he or she is doing is believable. This consequence of the nuclear age is irreversible.

The coercive power of nuclear bombs is the basis of their use by governments possessing them as a principal instrument of foreign policy. Might this same coercive power fall into other hands? Some people, apparently meaning to be reassuring, have argued that terrorists would pass up nuclear bombs in favor of other and perhaps simpler weapons of mass destruction, such as chlorine tankers (toxic at 15 parts per million) or pathogenic bacteria [Kupperman & Trent 1979:46]. These have in fact both been threatened by extortionists, and it is true that anthrax spores, claimed in a German extortion attempt [*id.*], are five orders of magnitude more toxic per gram than nerve gases and perhaps three orders of magnitude more lethal per gram than fissile material in crude bombs [*id.*:57]: their lethality could indeed "rival the effects of a thermonuclear device" [*id.*:46,65-68]. But it is the psychology, not the technology, of threats that explains why nuclear bomb threats have in fact outnumbered germ-warfare threats by better than twenty to one. (The existence of one vulnerability in society, moreover, is not an argument for creating yet another, but rather for seeking to reduce all of them.)

If fissionable materials had actually been made into an illicit bomb, that fact would probably be highly classified. Between October 1970 and November 1977 in the United States, however [Bass *et al.* 1980:55], there were 49 threat messages "in which adversaries claimed to possess nuclear material or a nuclear [explosive or dispersion] device and threatened to wreak severe damage with it." Such events doubtless continue; the press reported one, for example, in January 1979. Special procedures, evaluation teams, telephone numbers, etc. have been set up to deal with these threats, both at a Federal level and in some States (notably California). At least four threats were reportedly deemed sufficiently credible to evoke a high-level response, normally including an intensive search by a specially instrumented team [Singer & Weir 1979]. So far as is publicly known, all the threats have so far been bluffs, rather than representing actual devices which failed, or which worked and were hushed up. Again, so far as is publicly known, all the threats have so far been treated as bluffs, i.e. called. It is, however, hypothetically possible--there would be no way for the public to tell--that our government, or some other government,

has in fact capitulated to a non-hoax nuclear threat and is implementing, in the guise of normal incremental policy shifts, concessions dictated by an extortionist. The degree of openness and public trust normally associated with governmental affairs, at least in the United States, makes this hypothesis seem unlikely, but it cannot be altogether excluded; and certainly there is a lingering air of suspicion about apparent efforts, as the Comptroller General of the U.S. saw them, to block a full investigation of alleged thefts of bomb material in the mid-1960s [Burnham 1979a].

What could a terrorist who actually possessed a nuclear bomb do with it? Aside from obvious high-leverage targets* of a non-nuclear character (national monuments, centers of commerce, occasions on which many government officials are assembled, sports stadia, dams, refinery complexes, etc.), nuclear facilities offer a peculiarly attractive target because they can amplify the radiological effects of even a small, crude bomb by three to five orders of magnitude. Consider, for example, the effects of exploding a bomb near a power reactor. Chester & Chester [1976:329] state that cooling towers, without which the plant cannot operate, suffer heavy internal damage at about 2 psi overpressure, and will collapse at about 3 psi. At about 12 psi, "damage to the control room, auxiliary equipment, transformers, and water tanks will be so severe that it will be very unlikely that even an uninjured emergency crew could prevent destruction of the core." The containment shell (for ice-condensing PWRs) will be "badly damaged" and the primary coolant loop will probably suffer minor damage at about 30 psi, causing a major release within hours. The pressure vessel will rupture, releasing at least volatile fission products in minutes, at overpressures of the order of 150 psi. All these maximum overpressures are readily attained with small nuclear bombs at reasonable ranges. For example, a 1-kT (or 10-kT) surface burst produces peak overpressures of 150 psi at 85 (185) m; 30 psi at 220 (480) m; 12 psi at 390 (850) m; 3 psi at 980 (2170) m; and 2 psi at 1320 (2900) m. These yields will respectively evaporate of the order of 1000 or 10,000 tons of adjacent material, and have typical fireball radii (vaporization ranges) of about 75 m and 180 m.

These figures suggest that a major release can be guaranteed by arranging a groundburst even of 1 kT within hundreds of meters of the reactor, and a virtually complete release by shortening the range to the order of a hundred meters. At virtually any site, delivery trucks of dubious contents are routinely driven within closer ranges than these. Many sites would permit a 12-psi overpressure to be achieved by a kiloton-range bomb at standoff range from public highways. Even a fizzle might suffice: transmission lines and some diesel air intakes fail at about 4 psi, and this dual failure, unrepaired,

*If the bombing were anonymous, we would not know whom to retaliate against: the foundation of the strategic-deterrence doctrine would have vanished.

could cause a meltdown within hours. It is not realistic to expect repairs within the necessary period (at best an hour or two), because even a fizzle, say 0.1 kT, produces prompt radiation of 500 rem gamma at about 300 m, 500 rem fast neutrons at about 450 m, and 500 rem fallout dose in 1-hour exposure at 300-1000 m--all well beyond the moderate blast-damage range (3 psi) of about 300 m. It is thus an environment in which nobody could survive nor, having reentered, would wish to linger for repairs.

Prior to the work of Fetter & Tsipis [1980], as noted earlier, the potential use of small (e.g. terrorist) nuclear bombs on nuclear-facility targets had not been quantitatively treated in the literature. On the contrary, such analysts as Chester & Chester [1970,1974,1976] had considered relatively short-term effects from massive strategic attacks, so they naturally found that releases from reactors would not greatly increase the total destruction. Indeed, few analysts before Ramberg [1980] had thought seriously about the whole problem of power reactors in wartime. A few countries operating power reactors have had wars on their territory--India, for example--without involving the reactors. (In Vietnam, the 250-kWt TRIGA research reactor at Dalat was hastily dismantled by retreating American troops lest its radioactive core be released. Its 20%-enriched fuel was not considered a safeguards risk [Guardian 1975].) If attack threatened, would reactors be shut down, increasing safety at the expense of power supplies? More likely, as a Finnish nuclear expert said, "In a state of war the criteria for safety of nuclear power stations would change." [Flood 1976:33]

This issue, however, is likely to be taken more seriously following the Iranian (or Iranian-marked Israeli?) bombing of Iraq's nuclear research center on the outskirts of Baghdad on 30 September 1980 [Boston Globe 1980; Marshall 1980a] and the destruction of the Osirak reactor by an Israeli air raid on 7 June 1981. The deliberate targeting of the center--fortunately just before the large Osirak was first loaded with fuel--highlighted the possibility of major releases. The first raid also gave Iraq an excuse to deny access to IAEA inspectors [Koven 1980] who wished to satisfy themselves that the 12-13 kg of highly enriched uranium--enough for one or two bombs--which France had already reportedly delivered [Marshall 1980a], out of a planned consignment of 70 kg, was not being made into bombs. Senator Cranston has stated [Hume 1981] that he has "been informed by more than one authoritative Executive Branch official [that]...the Iraqis are embarked on 'a Manhattan Project-type approach'" to use the French uranium for bombs.

So far we have considered the vulnerability of nuclear facilities to crude nuclear bombs made from scratch by terrorists. But far more powerful and port-

able bombs may be obtainable from stockpiles made by the U.S. Department of Energy. There are some 7000 assembled U.S. bombs stored just in Europe, many small enough to tuck under one's arm*. One of them, set off near a nuclear facility, could spread as much fallout as a sizeable nuclear war. Nuclear facilities are thus such a high-leverage target that one must consider all routes by which terrorists might obtain a bomb. Many analysts who, unlike us, consider homemade bombs improbable give a good deal more credence to stolen ones.

Theft is certainly conceivable. Security, lax a decade ago, is still imperfect [Comptroller General of the U.S. 1980]. A respected analyst states [Barnaby 1975] that U.S. Army blackhat teams have successfully penetrated and left bomb storage bunkers without detection despite armed guards and modern barriers and alarms. Two incidents at a Nike Hercules base outside Baltimore suggest possible reconnaissance by potential bomb thieves [O'Toole 1974]. In 1979, journalist Joseph Albright testified [Dumas 1980:19] that by posing as a fencing contractor he gained an interior tour of two SAC bomb depots and their weak points: on 5 December 1977 he came "within a stone's throw of four...nuclear weapons" while "riding about 5 mph in an Air Force pickup truck...driven by my only armed escort [with one pistol, and both hands on the wheel....No one] had searched me or inspected my bulky briefcase, which was on my lap." Before publishing his article, he purchased by mail blueprints showing the depots' layout, a method of disabling the alarms, and two unguarded gates through the innermost security fence; afterwards he received a revised set showing "the wiring diagram for the solenoid locking system for the B-52 alert area."

*Can terrorists use stolen military bombs? Modern U.S. bombs--all those with Permissive Action Link (PAL) devices, which includes all those in Europe [Miller 1979:59]--can allegedly be detonated only by a proper numerical code, and repeatedly entering the wrong code irreversibly scrambles their electronics. This raises three questions unanswerable from open literature:

- Is it true that PAL-equipped bombs cannot be set off without a currently authorized code, even by the 50,000-odd people with up-to-date PAL training? DeNike [1975a] paraphrases Admiral La Roque as stating that "existing PALs malfunction often enough during practice drills that getting around them has become a regular practice. On any nuclear-armed U.S. Navy ship, there are four or five technicians trained to do this." If so, PAL is not tamperproof.

- Can a military bomb be carefully dismantled so as to recover its core? (And perhaps its other main components: any arming and firing circuits, and indeed everything else up to the detonators, could be readily replaced by an electronics expert.) For safety reasons, most if not all U.S. bombs apparently do not explosively disperse their cores if tampered with. Secretary Schlesinger stated in 1974 [Miller 1979:62] that "emergency destruction devices and procedures have been developed so that nuclear weapons may be destroyed without producing a nuclear yield in the event that enemy capture is threatened." But that is clearly not the same as an automatic anti-tampering safeguard.

- What are the corresponding safeguards in bombs made by other countries? It seems implausible that some, especially developing countries, will have developed the elaborate and very costly mechanisms used in modern U.S. and British bombs for command, control, and operational safety (including one-point safety, whose development alone reportedly cost billions of dollars).

The troublesome dimension which bomb stockpiles may add to existing nuclear vulnerabilities is relevant here because the stockpiles have already experienced enough mishaps to make theft, unauthorized use, or accidental detonation seem plausible. The rate of officially acknowledged "Broken Arrows" (nuclear weapons accidents short of nuclear detonation) has so far averaged about one per year or several per thousand bombs [Talbot & Dann 1981]. Over 30,000 bombs are now stored in up to 200 sites in over 40 states [*id.*]. Further, some 3-4% of the 120,000 or so carefully screened military personnel who have the opportunity to detonate nuclear weapons must be replaced each year--nearly 5000 in 1976 alone [Aspin 1977]--for reasons ranging from drug abuse (about a third of the total) to mental problems to negligence. Some reports [Dumas 1980] suggest that such problems may be increasing, especially those related to drug use. An Army demolitions officer and seven GIs, all drug smugglers, were arrested in Karlsruhe (coincidentally near a German nuclear research center with strategic inventories) after plotting arms thefts and a raid on an Army payroll office [*id.*]. February 1978 press reports describe a Georgia airwoman who broke and removed "four seals to the manual special weapons terminal handle" at a combat-ready B-52 guarded by soldiers with shoot-to-kill orders. French scientists testing a bomb in the Algerian Sahara apparently had to destroy it hurriedly lest it fall into the hands of rebellious French generals led by Maurice Challe [Brennan 1968], and during the Cultural Revolution in China, the military commander of Sinkiang Province reportedly threatened to take over the nuclear base there [*id.*]. Between theft, factions, unauthorized use, accident, and horizontal proliferation, it is no wonder some analysts expect, with Admiral La Rocque [De Nike 1975a], that "within ten years, we'll see an atomic explosion unauthorized by a government."

These issues are raised not with the intention of opening up the vast subject of American military policy, but merely to point out that the combination of numerous and widely dispersed bombs, nuclear facilities at which one bomb could mimic the fallout from a whole nuclear arsenal, and imperfect security, frailties, or temptations within the military could add up to disaster. A security system that could not detect a Klaus Fuchs at Los Alamos in wartime would be hard pressed to detect an unstable airman at some remote base in peacetime. Because nuclear facilities in the energy system can amplify the effects of one bomb by so many orders of magnitude, the risk latent in the inventory of bombs (and their production facilities) may contribute as much to total peacetime nuclear risk as all the civilian technologies considered earlier. If so, they ought logically to be subject to the same systematic scrutiny and the same types of efforts at hazard mitigation.

3.5. Policy trends.

This chapter has described some vulnerabilities of the energy systems on which all official projections of America's energy future place major and increasing reliance: oil, gas (including LNG and LPG), synfuels, and nuclear and coal-fired central power stations and their grids. These specific vulnerabilities, like the generic ones surveyed in Chapter 2, are inherent in the nature of the technologies. Some of the risks we have described may at first seem far-fetched--just as the hijacking of three jumbo jets to the Middle East in one week seemed implausible until it happened. But given the consequences, no one would wish to be in the position [Drobnick & Enzer 1981] of the British intelligence officer who, on retiring in 1950 after 47 years' service, reminisced: "Year after year the worriers and fretters would come to me with awful predictions of the outbreak of war. I denied it each time. I was only wrong twice."

In the coming decades, salient trends that can reasonably be expected to persist or intensify include: the nuclear and conventional arms races, East-West rivalries, North-South inequities and conflicts, global political fragmentation (often expressed as terrorism), domestic tensions and political polarization, unemployment, inflation, financial and climatic instability, and doubts about the vitality and reliability of global life-support systems. In such an environment of uncertainty, surprises, unrest, and possible violence, an energy system with built-in vulnerabilities to all these kinds of disturbances is a weakness we can no longer afford. Still less can we afford energy technologies which are prone not only to fail to deliver energy in these conditions--with all that implies for the potential of catastrophic breakdown in the comity and tolerance of our pluralistic political system--but to create in the process hazards to life and liberty as great as any hazards of war.

If a central tenet of national policy is to avoid placing ourselves in the position of having to choose between vital national interests, such unavoidably vulnerable energy systems are singularly unappealing unless there is absolutely no alternative. Happily, there are technologies and energy systems which not only are less vulnerable to all kinds of failures, foreseeable or not, but which also have other advantages--in cost, speed, ease, and attractiveness. We can choose technologies that safeguard both national security and the supreme interests which it embodies. As a basis for developing, in subsequent chapters, the elements of this approach, we begin in the next chapter with the rationale and principles of a design science of resilience--the theoretical foundations for designing an energy system consistent with national security in a free society.

4. DESIGNING FOR RESILIENCE

4.1. Resilience versus reliability.

As we noted at the end of Chapter 1, efforts to make the energy system reliable seek to enable it to withstand, or at least to make tolerably infrequent, calculable, predictable kinds of technical failure. But Chapters 2 and 3 have catalogued many incalculable, unpredictable kinds of disruption--by natural disaster, technical failure, or malicious intervention--which most of today's energy systems cannot withstand and were not designed to withstand. These systems were designed rather to work with acceptable reliability in what Alfvén [1972] calls a "technological paradise," where everything happens according to the blueprints. If such a place has ever existed, the world emerging in the coming decades is certainly not it.

Traditional analyses of the reliability of energy supplies have sought to assess the probability and consequences of failure. Too often, the probability cannot be calculated, and the consequences either are plainly unacceptable or cannot be adequately measured by such traditional measures as degree of degradation, direct economic losses, duration and difficulty of restoration, etc. Elaborately reductionist taxonomies have sought to classify how systems can fail. One, for example [Manly et al. 1970:100-103], classifies the "vulnerability" of a local economy to disruptions in its control, process, input, and output. Each of these in turn can suffer "principal physical losses," "network degradation," or "disruption from other losses or imbalances," each of many kinds; and so forth. But while this is analytically elegant, it offers no clue to how to design systems so they are not so vulnerable in the first place.

The vulnerabilities of complex systems often cannot be foreseen in detail. A decade ago, intensive efforts sought to identify and to calculate the absolute probability of various kinds of failures in hundreds of aerospace systems [Bryan 1974; Comptroller General of the U.S. 1974]. While some useful insights into the relative reliability of different designs did emerge, the absolute estimates wildly understated the actual failure rates. Fault-tree and event-tree methods predicted, for example, a failure rate of one per 10,000 missions in the fourth-stage Apollo engine, but the actual rate was about four per hundred. About 20% of the Apollo ground test failures and over 35% of the in-flight failures were of types not considered credible until they happened [id.]--just as the Browns Ferry and Three Mile Island accidents were of types not considered credible by the Rasmussen Report, which used similar methods. The sheer number of possibilities that must be examined makes such analyses intractable

unless they are severely truncated by assuming that enormous numbers of unanalyzed but allegedly "insignificant" terms are collectively insignificant. But in practice, many, perhaps most, accidents follow these unexamined sequences.

Another reason such analyses omit many actual causes of failure is that they assume complete knowledge. Design or fabrication errors which have not yet been discovered cannot be taken into account. Yet such errors caused a large fraction of the test failures in the Atlas missile program, about half the safety recalls of seven million U.S. cars in 1973, and a significant fraction of reactor mishaps. A recent review of 32 major accidents in reactors, aircraft, ships, trains, etc. [Solomon & Salem 1980] noted pervasive gaps in knowledge about the failure modes' identity, significance, consequences, likelihood, physical phenomenology, initiating events, and interaction with other factors (operating and maintenance errors, multiple random component failures, external events, etc.). So much is inevitably unknown that precautions against failure must be general enough to prevent failure modes that cannot be specifically identified in advance. Such precautions must embody resilience in the design philosophy, not merely reliability in the design details.

Large-scale failures which are physically possible will occur sooner or later as the passage of time tests all combinations of circumstances, probing for weaknesses. So many "vanishingly improbable" failures are possible that one or another of them is quite probable in a given year. Our foreknowledge of failure is limited only by the fertility of our imaginations, but the limits of our imagination do not affect what happens--only our degree of astonishment.

Traditionally, people have coped with inadequate knowledge by trial and error. But in the modern energy system, the cost of failure is so high that we dare not do this. The impossibility of foreseeing and forestalling all major failures to which the modern energy system is vulnerable--of preventing all surprises--requires that we take a different tack: learning to manage surprises and make them tolerable. This requires [Holling et al. 1979:2] an analysis of the unexpected: "of the sources of surprise, the perception of surprise and the response to surprise. From that, together with better understanding, come the possibilities of designs and developments that can absorb and benefit from surprise." For example, rather than just making Con Ed's switching relays more reliable in order to prevent an exact repetition of past catastrophic grid failures, this approach would seek to make the grid resilient--to make such failures structurally impossible, regardless of the initiating event, the sequence of failures, and whether or not they were foreseen. Equivalently, a strategy of resilience could seek to ensure that if complete grid failure did occur, its consequences to energy users would be trivial.

4.2. Passive versus active resilience.

This sought-after quality of "resilience" is difficult to define. The word is commonly used to refer only to what Kahn [1978:3] calls "ability...to withstand large exogenous [i.e. caused from outside] disturbances. The usual power system planning framework does not address itself to the occurrence of droughts, coal strikes or major inter-regional supply deficiencies. The ability to absorb such shocks gracefully has been called the 'resilience' of a system." But "resilience," he continues [:19], "...incorporates both a passive, behavioral notion and an active feedback control notion. A resilient system absorbs shock more easily than a 'rigid' system;" that is, when stressed it gives way gracefully without shattering. "This is a passive characterization. [But the]...corrective response to disturbance is an active control notion. In the case of power systems, the corrective response ultimately involves the political economy in which the [technical] system is embedded. Regulatory agencies institute investigations of major disturbances and initiate action to reinforce perceived weaknesses." Thus passive resilience is mere ability to bounce without breaking; active resilience also connotes the adaptive quality of learning and profiting from stress by using it as a source of information to increase "bounciness" still further. In the spirit of this metaphor, a rubber ball has passive resilience; the nerves and muscles of someone learning to play basketball have active resilience. Energy systems need both, but most currently have neither.

Kahn [1978] provides one of the few quantitative analyses of passive resilience by comparing the reliability of electrical supply from two hypothetical grids: one powered mainly by central thermal plants, the other by wind turbines. (For simplicity, the role of transmission and distribution systems is ignored in both cases.) Kahn focuses not on the relative size or dispersion of the power plants but rather on their reliability statistics--their "controllability" or intermittence. On simplified and probably conservative assumptions (favoring the steam plants), the two systems can be made equally reliable if the wind-dominated system is given slightly more storage capacity.

Kahn then asks not what might be the probabilities of various detailed failure modes, as traditional reliability analysts would do--the "highly specified network analysis and contingency enumeration approach" [:19]--but rather how the reliability of these two systems would change if each type of generation worked less reliably than expected. He "perturbs" the system by assuming worse performance all around, such as might be caused by a coal strike, oil embargo, generic nuclear shutdown, drought, cloudy or windless period, etc. The absolute amount of assumed degradation is the same for both grids, but in

percentage terms it affects wind less than central-station generators because the wind generators are already more subject to fluctuations: they are already intermittent and cannot get much more so. Their grid was designed to cope with fluctuation and has "bitten the bullet" by providing adequate windpower and storage capacity. But an equal amount of increase in the failure rate, whatever its cause, is far more serious for the central-station system, which was designed on the assumption of high reliability and rapidly breaks down without it. From the dispatcher's point of view, degrading reliability by 10% or more makes the central-station grid about five times less reliable than the wind-based grid. The central plants' storage or backup requirements to maintain equal reliability zoom up far more steeply and to much higher levels than those of similarly degraded wind plants. (Alternatively, if the reliability requirements were somewhat relaxed, the renewable grid could take more additional load than the central-station grid [:20], or equivalently would show a greater saving in backup or storage capacity.) This "supports the thesis associated with Lovins that the intermittent [sources]...produce a more resilient system" [:3].

Kahn thus finds [1979:343-344] that "the impact of unusual or extreme circumstances...modelled as extra [statistical] variance or uncertainty...[is] smaller...on the wind energy system than on the conventional one...[showing] a greater ability to absorb risk." He cites [id.] similar conclusions in the power-system control-theoretic literature and in a British wind-energy analysis by the Astronomer Royal, Sir Martin Ryle [1977]. Sir Martin's design for a British wind system was more resilient than that of the Central Electricity Generating Board [Leicester et al. 1978; Anderson et al. 1978] because it sacrificed a little performance at high windspeeds in order to be able to operate at low ones, and therefore could work most of the time. In a long period of low windspeed, Sir Martin's design would still produce power much of the time, while the CEGB's oversized machines would produce none at all, requiring over five times as much storage. The more "resilient system minimizes the impact of extreme conditions...." Such resilience "has important consequences. It means ...that exogenous uncertainties...have already been built into the system. Therefore the impact of the marginal risk goes down."

Passively resilient energy systems offer no benefit unless used. The process of learning to use them is a kind of active resilience. Biological systems have this learning and corrective process built in. It provides the adaptability that has carried these systems through several billion years in which environmental stresses were so great that all designs lacking resilience were recalled by the Manufacturer and are therefore no longer around to be studied. To understand active resilience so that we can apply it to the design of energy systems, we need to examine the architecture of biological systems that have survived the exacting test of evolution.

This is a central theme of several provocative articles by the Canadian ecologist C.S. Holling. He describes many instances in which the learning qualities of an ecosystem, not just its passive "safety margins" or its redundancy (like having an extra kidney), enable it to emerge strengthened by having experienced stress. Holling's arguments about biological resilience are framed in the language of abstract mathematics*, but at the cost of losing some of his subtler insights, we shall summarize them here in ordinary terms.

4.3. Resilience in biological systems.

Our earlier discussion (pages 17-18 above) of the Borneo and Canete Valley ecosystems found that when they were disturbed, unforeseen interlinkages within them made them lose their ecological stability. "Stability" in this sense does not mean a static equilibrium, but rather the ability of a system to regulate itself so that normal fluctuations in its populations of plants and animals do not reach the point of either extinction or plague. The system does not remain exactly the same--it is free to vary--but it varies only within one general mode of behavior that is recognizable and coherent.

Self-regulation that works only so far is common in biological systems. As Garrett Hardin has pointed out [Holling & Goldberg 1971:225; emphasis added], our bodies regulate their own temperature at about 98.6°F. "If through sickness or...dramatic changes in external temperature, the body temperature begins to rise or fall, then negative feedback processes bring [it] back to the equilibrium level. But...this regulation occurs only within limits. If the body temperature is forced too high...the excessive heat input defeats the regulation,...[increasing] metabolism which produces more heat, which produces higher temperatures, and so on. The result is death. The same happens if temperature drops below a critical boundary. We see, therefore, even in this simple system, that stability relates not just to the equilibrium point but to the domain of temperatures over which true temperature regulation can occur. It is [the breadth of] this domain of stability that is the measure of resilience."

*A new branch of mathematics known as "catastrophe theory" [Thom 1975; Stewart 1975; Woodcock & Davis 1978] deals with discontinuous changes in the state of complex systems. It is able to classify these changes--which can be, for example, only of seven basic kinds in a system controlled by four variables--and can describe them by geometrical analogies. (Strictly speaking, the style of mathematics is more that of topology, which deals with the most general properties of geometric forms, such as how many holes they have through them, without being concerned with their exact size or shape.) Holling's results do not rely on the theorems of catastrophe theory, but do borrow some of its terminology. Readers with good mathematical intuition are urged to read Holling in the original [1978; Holling et al. 1979].

More complex systems with more variables also have their domains of stable self-regulation beyond which they break down. Regardless of the degree of complexity, successful (i.e. surviving) ecosystems "are those that have evolved tactics to keep the domain of stability, or resilience, broad enough to absorb the consequences of change." [Holling & Goldberg 1971:225; emphasis added] These systems do not attain the absolute pinnacle of biological efficiency in capturing available energy, but by avoiding the extreme specialization this would require, they also avoid the risk of "contraction of the boundaries of stability"--a reduced margin of adaptability.

Holling [1978:99-104] describes several possible ways to view these "domains of stability" and hence to judge the resilience of an ecosystem. For example, one mathematically simple and politically comforting view, widely held by non-biologists, is that the domains of stability are infinitely large--that nature is infinitely resilient, tolerant, and forgiving. In this view, no matter how drastically a system is disturbed, it will always bounce back.

An opposing view holds that nature is so delicately balanced that the domains of stability are infinitely small, so that any slight disturbance will lead to extinction. If this were literally true, hardly anything would be left alive. But this view is not so indefensible if applied only locally, not globally, because then temporary extinction in one place can be made up by recolonization from adjacent areas. Some classical experiments in population biology illustrate this process. For example, if two kinds of mites, one eating plants and the other eating the first kind of mite, are confined within a small area, both the predator and the prey populations will drop to zero as their oscillating interactions outrun their respective food supplies. But if the enclosure is divided by barriers into sub-regions, between which either kind of mite can move with some delay and difficulty, then since the population cycle of outbreak and collapse proceeds at slightly (and randomly) different rates in different sub-regions, both the predator mites and their prey can recolonize from surplus to deficit areas. This ensures the survival of both species someplace in the enclosure. That experiment illustrates the important conclusion that if domains of stability are small--if a system is fragile--it will benefit from being fine-grained and heterogeneous in space. Failure then does not propagate and can be repaired from areas still functioning. Local backup, local autonomy, and a preference for small over large scale and for diversity over homogeneity all increase resilience in such cases.

A possible view precisely between the extremes of supposing nature to be infinitely brittle or infinitely resilient is the view that the behavior of ecosystems is neutral, tending toward neither stability nor instability, and neither endangered nor protected by general features of system architecture.

The coupled differential equations commonly used to represent the interactions between two populations embody this view by assuming that the populations can fluctuate without limit, influenced only by each other. This view, again, is mathematically convenient but greatly oversimplified. If it is refined by adding any kind of negative feedback (for example, that population outbreaks will be constrained by crowding effects), then collapse becomes impossible. On the other hand, adding any kind of positive feedback, or time lags in responding to events, creates instability and makes collapse inevitable. Yet both negative and positive feedbacks actually exist in real ecosystems, leading to a mix of stabilizing and destabilizing properties whose relative dominance varies in time and space. It is the balance of these stabilizing and destabilizing forces that enables ecosystems to regulate themselves into a semblance of stability--provided they are not pushed too far, into a region of behavior where the instabilities dominate and cause collapse.

In all but perhaps the simplest ecosystems, these mathematical properties create (as both theory and experiment confirm) not just one domain of stability, or region of equilibrium behavior, but multiple domains of stability. Each represents a "basin" within which the behavior of the system can "slop around" without dramatic change. But if some variable important to the system's behavior exceeds its range of stable values, the system can abruptly change into a different "basin" of behavior by "slopping up over" the "ridge" between adjacent "basins." Eutrophication of a pond is such a change. If more and more nutrients (e.g. phosphates) are added to the water, eventually its limits of tolerance will be reached. It will suddenly develop an algal bloom, which can lead to rotting of the plant matter and the irreversible creation of anerobic conditions. The pond can then not support its original species or perhaps any others. Similarly abrupt transitions, triggered by seemingly small disturbances to critical variables, can apparently occur in marine biology [Platt et al. 1977], in global climate [Lorenz 1976], and even in political and economic systems (as in the Great Depression, revolutions, and similar cataclysms).

If ecosystems have multiple domains of stability and can be easily triggered to switch from one to another, the strategy for avoiding such a transition is to stay far away from the "ridge" separating one domain or "basin" of stability from the next. This is precisely, as Holling [1978:102f] remarks, "in the highly responsible tradition of engineering for safety, of nuclear safeguards, of environmental and health standards." But, to add emphasis, this approach "demands and presumes knowledge". It works beautifully if the system is simple and known--say, the design of bolts for an aircraft. Then the stress limits can be clearly defined, these limits can be treated as if they are static, and the bolt can be crafted so that normal or even abnormal stresses

can be absorbed. The goal is to minimize the probability of failure. And in that, the approach has succeeded. But in parallel with that achievement is a high cost of failure--the very issue that now makes trial-and-error methods of dealing with the unknown so dangerous. Far from being resilient solutions, they seem to be the opposite, when applied to large systems that are only partially known. To be able to identify...[safe limits]...presumes sufficient knowledge." Thus the engineering-for-safety approach "emphasizes a fail-safe design at the price of a safe-fail one." If the inner workings of a system are not perfectly understood and predictable, efforts to remain within its domain of stability may fail, leading not to safety but to collapse.

Worse, because the hidden processes and parameters that determine the size of that domain are continually (if slowly) changing in time, and because they may interact with outside influences in ways that may not be perceived in advance, changing the values of key parameters in a well-meant effort to ensure safety may actually create new dangers. Intervention can "shrink" or even "implode" domains of stability, throwing the system unexpectedly into unstable or catastrophic behavior modes--just as spraying pesticides in the Canete Valley made a previously resilient ecosystem too brittle to cope with normal fluctuations in growing conditions.

If the position of each stability boundary could be perfectly known and the distance to it monitored and controlled, safety might be possible. But in the absence of perfect knowledge, efforts at such control are more likely to shrink the domain of stability and to shift its boundaries in unexpected directions. The WHO thought it was using safe levels of DDT in Borneo, but not that this intervention, focused on providing a narrow form of safety--eradication of malaria--would so destabilize other interactive predator-prey relationships as to result in plague. "This dynamic pattern of the variables of the system and of its basic stability structure," writes Holling [1978:104], "lies at the heart of coping with the unknown."

Striving merely for passive resilience--"the property that allows a system to absorb change and still persist"--means striving to stay away from the boundaries of stability. Yet as interventions and environmental changes constantly shift those boundaries, actions that used to be stabilizing may become destabilizing, and far-off boundaries may become near or be transgressed. A strategy mindful of the limits of knowledge, therefore, is to strive for active resilience--"a property that allows a system to absorb and utilize (or even benefit from) change." This approach implies very different management methods: for example, environmental standards loosened or tightened according to the needs of the stressed ecosystem. It places a premium on adaptation--on making time constants long for dangerous changes and short for measures responding to them.

Ecosystems achieve active resilience partly by their layered structure of successively more complex and specialized organisms. Low-level layers contain a relatively large number of relatively small components with different functions. The integration of these components produces or supports the next higher layer, as in a food chain. Successively higher layers cover a larger area and work more slowly. Within this complex structure, at each level, "the details of operations [among] the components can shift, change, and adapt without threatening the whole" [id.:105-106]. For example, ecosystems use many overlapping populations to perform the same function, such as primary production, partly because of uncertainty: since sunlight is not uniform, for example, a diverse forest may contain both sun-loving and shade-tolerant plants. "Any particular function represents a role that at different times can be performed by different actors (species) that happen to be those available and best suited for the moment." [:105-106] The mathematics of hierarchical structures allows rapid evolution and the absorption and utilization of unexpected events."

The importance of a layered structure is illustrated by an anecdote about the different working methods of two imaginary Swiss watch-makers [id.]:

One watch-maker assembles his watch as a sequence of subassemblies--a hierarchical approach. The other [merely]...builds from the basic elements. Each watch-maker is frequently interrupted by phone calls and each interruption causes an[y incomplete] assembly to fall apart....If the interruptions are frequent enough, the second watch-maker, having always to start from scratch, might never succeed in making a watch. The first..., however, having a number of organized and stable levels of assembly, is less sensitive to interruption. The probability of surprise (of failure) is the same for each. The cost...is very different[, in that one maker is able to finish building watches while the other never can].

...[M]issing steps in a hierarchy will force bigger steps [which] take a longer time [and]...presume the greatest knowledge and require the greatest investment. Hence, once initiated, they are more likely to persist even in the face of obvious inadequacy. Finally, bigger steps will produce a larger cost if failure does occur. To avoid that, the logical effort will be to minimize the probability of...of surprises or of failures.

For example,...a number of watch-makers [might]...join together, pool their resources, occupy a large building, and hire a secretary to handle the phone calls. This would control the...interruptions and both watch-building strategies would succeed. Without the interruptions, there is not that much to gain by maintaining very many steps in a hierarchy of subassemblies. [Having fewer steps between larger subassemblies]...might increase efficiency and produce economies of scale but is totally dependent on complete and invariant control of disturbance. If the secretary were sick for one day production would halt.

Imitating the strategy of successfully resilient ecosystems, then, may not wring out the last ounce of "efficiency" or attain the acme of specialization that might be optimal in a surprise-free world. But in a world of uncertainty, imperfect knowledge, and constant change, that strategy does win an even richer prize--minimizing unexpected and disastrous consequences [Holling & Goldberg 1971:229] which can arise when the causal structure of a real system turns out

to be qualitatively different than expected. Holling *et al.* [1979] illustrate the dangers of narrowly "efficient" interventions with five practical examples:

- Spraying to control spruce budworm in eastern Canada. This protects the pulp and paper industry in the short term. But the populations of budworms, their avian and mammalian predators, tree foliage, etc. are continually changing anyhow on many different time-scales, with fast, intermediate, and slow variables. Spraying disturbs only the fast variables, sending an intricate web of dynamic relationships into a new behavior mode: reduced tree growth, chronic budworm infestation, outbreaks over increasing areas, and--if spraying stops--high vulnerability "to an outbreak covering an area and of an intensity never experienced before." The sprayers' mental model has one element--that spraying kills budworms, which eat trees, which are worth money--whereas even the simplest successful simulation models of the system have thousands of variables.
- Protecting and enhancing salmon spawning on the west coast of North America triggers increased fishing and investment pressure to profit from the larger harvest. These extinguish less productive stocks and leave fishing "precariously dependent on a few enhanced stocks that are vulnerable to collapse."
- Suppressing forest fires in U.S. National Parks succeeds in the short term, but also accumulates unburned fuel which leads inevitably to "fires of an extent and cost never experienced before."
- Transforming semi-arid savannah into productive cattle-grazing systems in parts of the U.S., Africa, India, and Australia also changes the grass composition so as to cause an irreversible switch to woody vegetation. The resulting altered ecosystem is highly susceptible to drought-triggered collapse.
- Some malarial eradication programs have succeeded only long enough to produce DDT-resistant mosquitos and human populations with little immunity, leading in turn to greatly intensified outbreaks.

In each of these examples, like the Cañete Valley spraying mentioned in Chapter 1, a problem was made worse by defining it more restrictively than the interactive nature of the ecosystem permitted. Intervention shrank, shifted, or destroyed the original ecosystem's stability domains, making behavior "shift into very unfamiliar and unexpected modes" [:27]. Some disturbed systems "forgot" their previous history and became "more sensitive to unexpected events that previously could be absorbed."

Holling *et al.* conclude that when ecosystems turn out to be unexpectedly complex, leading to apparently unpredictable side-effects, the institutions responsible tend to respond in one of three ways:

First[,] they may try to design away the variability by deliberately simplifying the system and/or its environment [e.g. by seeking to eradicate predators, "pests," or "weeds"--often with intractable side-effects].

Second, they may try to extend the boundaries of definition of the natural system, so as to include "all relevant factors" in their analyses [via elaborate models and large interdisciplinary research groups--an approach equally doomed to failure but slower to appreciate it]....

Third, they may simply try to find ways to live with high variability. There are at least two design possibilities for living with surprise. First, the institution may attempt to design some means to stabilize system outputs without stabilizing system states, by finding some way to store up outputs and release them in a more or less steady stream. Individuals hedge against uncertainty by storing money in savings accounts; dams store water for release in dry periods....This design approach is the most promising, in terms of social acceptability, that we have uncovered so far. Finally, the institutions may attempt to spread risks by disaggregating the system into 'operational units,' each with a relatively low cost of failure [and minimally interdependent on each other]....For example,...the energy planner must be able to design parallel development...options...such that failure of one does not drag the others down also.

Subsequent Chapters will expand on these last two approaches--smoothing and disaggregating energy supplies. They are indeed the "most promising" approaches for making tolerable those surprises that cannot be reduced to expectations.

4.4. Design principles for resilience.

Designers of aircraft, reactors, military hardware, water and telecommunications systems, etc. have long sought to achieve at least passive resilience--to avoid the "brittleness" of systems that shatter if stressed beyond their limits. In this quest they have developed by trial and error a number of tacit principles of design. (We say "tacit" because few have been written down. Classic texts of reactor engineering [e.g. Thompson & Beckerley 1964-70] have far more to say about specific design embodiments which may be resilient than about the general principles of formulating such designs, and even such acknowledged experts in resilient design as F.R. Farmer and S. Hanauer do not seem to have formalized their extensive design experience.) These principles mirror those used in biological organization to achieve active resilience.

The elements of resilient design can be described qualitatively, but are exceedingly difficult to pin down in numbers. They are also not all mutually consistent and compatible, so some compromises between them are necessary--a process with which living things are not yet fully satisfied after several billion years, so it will doubtless take human analysts quite a while too. Deferring to Chapter 5 the fuller discussion of issues related to the scale and decentralization of individual components of the energy system, we consider here the broad principles of dispersion, numerical redundancy, functional redundancy, diversity, interconnection, functional flexibility, modularity, standardization, internal decoupling and buffering, simplicity, forgivingness, reproducibility, speed of evolution, accessibility, and social compatibility.

Dispersion has long been a cardinal rule in military tactics--not bunching up all one's forces in vulnerable concentrations. The military value of dispersing energy sources is illustrated by the examples we reviewed on pp. 49-50, notably the case of Japanese hydroelectricity in World War II. Dispersion of industrial facilities was recommended in the U.S. in the first post-Hiroshima strategic review [Joint Committee on Defense Production 1977:I:99] and is considered desirable, if not always practiced, in the USSR [id.:II:75-77]. Geographic dispersion means that if a mishap occurs in a particular place, it is more likely that some units will be there but less likely that they will all be there, so the maximum simultaneous loss is reduced. Dispersion on a sufficient scale (typically hundreds of miles) can smooth out local weather fluctuations: it increases, for example, the average net output of an array of wind machines [Kahn 1979:320], because although they may not all be exposed to high winds at the same time, neither are they likely to be simultaneously becalmed.

Dispersion does not necessarily imply small unit scale. (Appendix C explains the complex semantics of such terms as "decentralization.") Dispersion refers only to the degree of geographic concentration of units, and hence may refer only to remote, scattered siting of a few large units. Only by spreading out a relatively large number of relatively small units can one obtain most of the reduction in vulnerability exhibited by e.g. the Japanese hydro example. With dispersion and small unit scale, the number of users affected by any one failure will be small, so each unit will be a low-priority target and its failure of less social consequence. Regardless of unit size, dispersion can provide a local source of supply for nearby users--though it need not, as shown by the notorious case of Native American settlements in sight of the Four Corners power plant but still without electricity. But if units remain large, "dispersion" means remoteness from those users away from whom the units were dispersed. This requires those users to rely on a farflung distribution system which may increase total vulnerability. We return to this point below.

Numerical redundancy means having extra capacity so that one unit can back up or replace another. It is easiest with small, relatively cheap units. It is a familiar method of improving technical reliability. Because its extra costs are clearly visible, it is often ignored, as in many giant oil tankers whose steering and other vital functions depend on unreplicated steam sources [Mostert 1974]. Even military hardware, not noted for cost-shaving, sometimes makes the same mistake: DD-963 class destroyers, for example, have waste heat boilers that are "extremely difficult, if not impossible[,] to...maintain. Equipment failure would result in partial loss of ship's electrical power, potentially affecting ship's weapon systems"--a sign of inadequate backup [Comptroller General of the U.S. 1981:61].

Numerical redundancy can cause complications. If it needs a "voting system" to reconcile signals from redundant guidance computers or gyros, failure of the "voting" device can disable all redundant channels simultaneously. Further, the simplest form of numerical redundancy (replicating identical devices) risks common-mode failure, as we mention below: any number of supposedly redundant diesel generators can be disabled by identical design or maintenance faults, contaminated fuel, etc.* Replication without isolation is equally imperfect. The DC-10's multiple hydraulic cables were routed parallel to each other throughout the aircraft, so that a single event (the collapse of the cabin floor when an open cargo door depressurized the hold in the Paris crash) could cut all the lines and thus disable the whole plane's hydraulic control system.

Functional redundancy, as John von Neumann christened it, addresses these problems by carrying out a given function "in parallel by a number of functionally identical but physically very different subsystems. A specific example would be coupling inertial guidance, fluidic, and electronic subsystems into the guidance system of a missile. Destruction of the electronic components by a nearby intense radiation field would not damage the purely mechanical components, permitting the function to continue. Although this example is not a happy one to contemplate, it demonstrates [that] where systems are considered by their designers to have to succeed in the face of multiple assaults, techniques for creating a high degree of resilience have been used." [Weingart 1977:29]

It is on the principle of functional redundancy that nuclear reactors shut down if any of several signals is abnormal (e.g. neutron flux, temperature, or period); but translating that shutdown command into action may fail for lack of diversity. Most reactor shutdown systems in the U.S. rely on continued electrical supplies from the plant busses. In contrast, British practice favors many functionally redundant shutdown devices, relying perhaps on centrally powered electrical devices in one case, local battery power in another, gravity or springs in another, and local compressed-air bottles in yet another. This diversity is sought quite deliberately, on the principle that one's inability to think of a failure mode for a particular system does not mean the system cannot come up with one, so having systems as different as possible may help in some unforeseen way to protect against common-mode failure*. Likewise, an important

*Strictly speaking, common-mode failures can be distinguished from common-cause failures [Solomon & Salem 1980]. The former refer to the failure of identical, numerically redundant components in the same way, while the latter refers to a failure of functionally redundant systems from a common initiating event. Although our argument does not depend on this sometimes forced distinction, both kinds of failures tend in, say, reactor accidents to be more important than random, sequential failures of single components. Common-mode failures need not be purely technological: the same political trends could simultaneously prevent Western coal, oil-shale, synfuel, power-plant, water, and uranium projects.

strand of the nuclear safety debate concerns the ways in which functional independence can be compromised by links between primary and backup systems. Westinghouse reactors, for example, commonly activate safety systems with the same signals that control normal operating systems. This link has on occasion prevented both systems from working--leading a senior NRC advisor, Dr. Stephen Hanauer, to note, "Westinghouse thinks this [interconnection] is great [because it saves them money]. I think it is unsafe. This has been going on for years."

If badly done, functional redundancy can appear to be an operational nuisance. In graphite-moderated reactors, for example, some types of accidents might distort the core so that control rods can no longer be fully inserted. In the newer British reactors, an emergency shutdown system known as the "O Jesus" system is therefore provided to blow boron dust into the core with pneumatic hoses; this would require that the reactor be written off, but at least would ensure shutdown. Coupling up the hoses takes long enough that it cannot be done thoughtlessly or accidentally. In contrast, the Fort St. Vrain reactor in Colorado uses instead hoppers of boronated steel balls which fall down into holes in the moderator if the current to magnetic latches is interrupted. An accidental activation of this system left the operators spending reportedly the best part of a year vacuuming the balls out again. The principle--ability to shut down by other means if mechanical rod insertion failed--was sound; but because its execution was flawed, it gave the principle a bad name.

Examples of more successful technical diversity abound. In emergency broadcasting and telephone facilities, for example, diesel generators are commonly backed up not by other diesels but by batteries. In nuclear warheads, functionally redundant proximity and barometric fuses are backed up by a simple salvage fuse to ensure detonation on hitting the ground. Diversity need not be purely technological: entering Minuteman silos requires combinations held by both the security and maintenance staff, but many of the security staff are Oriental in order to make apparent any unauthorized association with the maintenance crews, who are mostly Caucasian. Conspiracies for unauthorized entry thus become more difficult and conspicuous to arrange.

Diversity, properly established, enables a system to work even without unique skills, materials, institutions, fuels, etc. which it would normally need, because some backup element can do the same task without that input. If a spare part is not available for a diesel, the batteries can take over meanwhile. On the other hand, diversity may complicate support logistics by requiring a wide range of small-volume inputs for normal operation and maintenance: one must provide not only diesel parts and fuel but also battery acid and spare plates. Only technical simplicity (see below) helps to reduce this burden.

Interconnections between energy sources and users provide a rich menu of advantages and dilemmas. On the one hand, interconnections essential to a system's operation can actually propagate its collapse (as in the electric grid failures we reviewed earlier). On the other hand, interconnections can prevent collapse, bring help later, or enable one source to back up another (as in the wheeling of coal power to oil-short areas*). At the best of times, interconnections require continuous and meticulous management, especially in synchronized electrical grids [Subcommittee on Energy & Power 1977:116-117]. The ideal kind of interconnection, as our Finnish example on page 52 suggested, is an optional one which permits the reliability and economic advantages of grid connection but which also permits local units to isolate from the grid at need and continue to power their local service areas (p. 156 below).

Studies of the vulnerability of electric grids [e.g. Lambert & Minor 1975] show the virtue of a rich topology of interconnections and of avoiding big, "lumpy" nodes--points of either supply or interconnection--which would tend to concentrate the probability and consequences of failure. That is, a number of energy sources that can route their output via many different paths of roughly equivalent capacity, diffusing the risk rather than relying unduly on particular sources or conduits, can usually deliver it somehow to where it is needed. Many U.S. electric transmission and distribution systems lack this property: their interconnections are too sparse or their capacity is too "lumpy" (undistributed) to spread the risk. In contrast, battleship designers, knowing that parts of the ship may be damaged in a battle, ensure that multiple electric busses located in different parts of the ship, and each with extra capacity, can be hooked up in many different permutations to improvise continued supplies.

The Bell System provides a useful analogy here. Telephone trunk transmission is very highly interconnected; long-distance calls are commonly rerouted, even several times a second, without the caller's noticing. Loss of a particular microwave, satellite, or cable link can generally be compensated by use of others. But on closer examination, as "phone phreaks" are discovering, this flexibility of rerouting calls actually depends on a relatively small number of key switching points. By tying up all the input ports at these points, a small group of knowledgeable people could crash the Bell System. It is indeed the very openness of the telephone network, allowing ready access from innumerable points, that helps to cause this vulnerability (to say nothing of allowing the KGB to intercept essentially all transcontinental phone traffic). Most people are aware of the peculiar vulnerabilities of the phone system only if their own call happens to be cut off by some mishap--perhaps that a tone in their voice was too close to the frequencies used to signal for cutoff--but all they

*And vice versa: 15 TW-h was imported in the 1977-78 coal strike [NERC 1979:7].

normally lose is their own call, not everyone's at once. Yet as able, computer-equipped "communications hobbyists" probe these vulnerabilities, out of malice or mere curiosity, we may all become more aware that the routing flexibility of the Bell System is not as invulnerable as it looks. It is an open question whether the apparent flexibility of routing in major electric grids is equally vulnerable to disruption of a few key nodes. Although some observers think not [e.g. Joint Committee on Defense Production 1977a:72-73,116-117], it is not clear that they have thought very hard about it.

Related to functional redundancy, and often reliant on interconnection, is the property of functional flexibility. The human body provides numerically redundant kidneys, lungs, etc., plus considerable spare capacity in the liver and heart, but there is only one spleen. No matter: if the spleen is lost, certain structures in the liver are sufficiently similar that the liver can gradually take over the spleen's essential functions [Altman 1980]. That is, although not meant to be a spleen, the liver is designed to pinch-hit for it. This is the concept behind the Swedish requirement that new boilers be able to accept solid fuel (coal, wood, etc.) and the recent Swedish government discussions on whether to stockpile wood gasifiers for emergency operation of cars--a highly developed art that ran a million motor vehicles during World War II. Not content with requiring boiler operators and other principal energy users to maintain private stockpiles amounting in practice to about 0.8 years' fuel supply, the Swedish government is already thinking about pinch-hitting technologies. The same principle presumably guides U.S. planners' Multi-Fuel Program to make military vehicles adaptable to a wider range of emergency fuel supplies--a flexibility the Third Reich found essential, equipping by March 1944 more than 80% of large vehicles to burn alternative liquid, gaseous, and solid fuels [Energy & Defense Project 1980:23]. Such flexibility can apply to both energy supply and demand, and Chapter 6 will illustrate how more efficient energy use can make improvised supplies vastly more useful.

Modularity and standardization are double-edged properties: on the one hand, the ability to plug in common replacement parts can make equipment far more maintainable, but on the other, if the modules happen to incorporate a design or manufacturing flaw, that flaw is then plugged in universally--as has occurred with certain automobile spare parts. Special care is thus essential (if not always sufficient) to prevent the propagation, by a well-meant program of standardization, of proneness to common-mode failures.

A technology which comes in relatively small constituent blocks is flexible in size and often in function and location. It is more portable, more easily cannibalized and transferred, easier to experiment with. It is also likely to

be more maintainable. (Maintainability is not the same thing as being super-reliable--an essential property where failure is intolerable, but not an ideal property because it means that failures are so infrequent that people may not have enough hands-on repair experience to be able to fix them properly.)

Internal decoupling and buffering is an essential feature of resilient systems. It means that their parts should be only loosely coupled in time and space, so that the failure of one does not immediately disable others. An oil refinery, for example, which has very small storage tanks in between its stages has no operational flexibility: if all stages do not work exactly at the rate and in the manner planned, products will be too scarce at some points and too plentiful at others. If one stage fails, there will also be no way to bypass it and no "breathing space" of time in which to improvise repairs, so the whole plant will have to be shut down [Stephens 1970:105;1973:112,34]. This principle is well-known to chemical process designers, but not always observed: one of the reasons the G.E. reprocessing plant at Morris, Illinois had to be written off as inoperable was that it was too tightly coupled to allow for normal operational variations among its sequential stages. The general principle of stretching the time constants of a system--leaving "slop" between its stages to allow rerouting, modification, and repair--is considered further in Chapter 6. Meanwhile, it is important to note that if the storage of fuels or energy can be dispersed and located near the end-users, it provides them with a long time constant in case they are interrupted. Similar considerations apply in non-energy industrial systems: the British auto industry, for example, holds only small buffer stocks of steel (for "efficiency") and so is rapidly halted by steel strikes.

Another desirable technical feature of energy systems and components is simplicity. Experienced engineers have long worked by the KISS principle ("keep it simple, stupid") and the Fathy principle ("Don't try to improve on anything that works"); but some engineers are tempted to forget the truism that the fewer components there are, the less there is to go wrong. Boeing-Vertol's first design for a door for Boston subway cars had 1300 parts, later reduced to 300: the designers were so sophisticated that they couldn't design a door any more. (They also showed their oversophistication by designing a floor whose rigidity would have been ample on an airplane, with passengers sitting neatly in rows; unfortunately, subway riders cluster at the doors on arriving at a station, and this redistribution of weight so bowed the floors that the doors jammed shut.)

Simple mathematics requires that very elaborate systems break down often. A system whose operation depends on 10 components, each of which works 99% of the time, will be out of action 10% of the time; with 100 such components, 63% of the time; with 1000, 99.9957% of the time, so it will work only 23 minutes

per year. The Navy's MK-86 fire control system, used on the most advanced combat ships, doesn't work about 40% of the time--partly because it has over 40,000 components. (Not surprisingly, it is proving very difficult to stock enough spare parts and train the repair personnel.) [Comptroller General of the U.S. 1981:6] To be 96% reliable, a system whose operation depends on each of 40,000 components must have an average component reliability of 1 failure in a million. The MK-86's average component reliability is apparently some ten times worse.

If the potential for common-mode failures is somehow related to the number of possible interactions between any two components, and if those interactions can be of only one kind, then the number of interactions among n components is $n(n-1)/2$ --or, for 40,000 components, some 800 million. But if interactions can be between more than two components, or of more than one kind, then the number of interactions rapidly becomes astronomical*.

In the face of such discouraging mathematics, resilience requires that nothing important depend absolutely on anything complicated unless its complexity is very thoughtfully organized†: the price of failure can simply be too high. When the sophisticated MK-86 fire-control system works, it can simultaneously track and destroy multiple incoming missiles. But when it fails (i.e. 40% of the time), "the ship is virtually defenseless" [id.] and can be destroyed by a single shot. A more brittle design can hardly be imagined. Sometimes, however, there is a better choice. Some years ago, there was reportedly a debate in the Pentagon about which of two control designs to buy for a major missile system: a rigidly hierarchical one which worked only if all its subsystems worked, or one with less monolithic architecture, designed so that it would work even if about a third of its subsystems were out of action. The former was selected because it looked about 10% cheaper. (In the event, the missile was not built anyway.) Today, after more experience of unreliable weapons systems [Fallows 1981], the decision could well be different.

A desirable property well-known to designers, but hard to characterize formally, is forgivingness. Although, as Edward Teller remarks, no foolproof system is proof against a sufficiently great fool, a "forgiving" system at least tolerates the ordinary run of foolishness. A "forgiving" design is simple and robust enough to tolerate mistakes and variations in design and manufacturing;

*Power reactors have already reached this stage: safety systems sometimes interfere with each other or even initiate accidents by their unforeseen interactions. The limits of tolerable complexity may, in the view of some thoughtful analysts of nuclear safety, have been reached and exceeded: simpler systems cannot do the job (at least given the types and sizes of reactors now in use) while complicated ones can behave in ways beyond our ability to predict.
 †Even complex systems can be reliable and resilient if their many components are organized "in such a way that the reliability of the whole...is greater than the reliability of its parts" [von Neumann 1956], e.g. via decentralized control systems acting in parallel [Šiljak 1978; Barlow & Proschan 1975].

it may also isolate or limit the effects of failure. An "unforgiving" design pushes materials and components so near their limits of performance that any deviation from expected perfection leads to serious failure. The collapse of many box-girder bridges (a style of construction once popular in Britain) has been traced [Stewart 1975:450], using catastrophe theory, to the use of design techniques and structures (stiffened panels) which "are maximally sensitive to imperfections in their manufacture": their buckling behavior is such that even slight deviations "can reduce the strength to around two-thirds of the theoretical maximum." Result: several deaths and hundreds of million dollars' damage.

A bridge design that had large safety margins because of the shape of the components--not just the plentiful use of materials--or that was so designed that failure could not propagate from one part to another would be inherently "forgiving." In this sense, a typical LNG tanker is an "unforgiving" design because one breach of the LNG containment membrane may lead to failure of the entire hull. A low-power-density, high-thermal-mass nuclear reactor whose nuclear reaction is damped by higher temperatures is more "forgiving" than one which has the opposite properties and therefore allows only a short time to correct deviations. An aircraft that can land safely with all engines out is more "forgiving" than one that cannot. A spacecraft that can be safely navigated and landed without its guidance equipment, even by the use of such old-fashioned equipment as a sextant, is more "forgiving" than one whose survival depends on its electronics [Cooper 1973].

It should go without saying that energy systems are more resilient if they rely on sustainable, renewable energy flows not subject to depletion or deliberate interruption. It is perhaps less obvious that such systems should also be reproducible without elaborate resources. A nuclear power reactor is not only among humankind's most complex technological achievements; it also depends for its construction and its continued maintenance on a pool of highly specialized skills, processes, and materials. If there is no longer enough business to keep those resources employed, well-trained, well-motivated, and continuously recruited at a high level of talent--as appears to be the prospect for the nuclear industry over the coming decades--safety and maintainability may decline. Conversely, a wind machine simple enough to made in any vocational school shop, and which will run without maintenance for twenty or thirty years, is a sufficiently "vernacular" technology* to be accessible to a wide range of people and operable even under highly disrupted conditions. Later Chapters will explore further the availability of such simple, readily buildable and operable technologies, and the contribution they can make to energy preparedness if necessary information, skills, and materials are properly dispersed and stockpiled.

*This phrase is due to Illich [1980].

A technical feature conducive to resilience, though seldom considered in this regard, is capacity for rapid evolution. Biological succession, including that of dinosaurs by small mammals, has depended on the rapid exchange of genetic information, trial of new designs, and feedback from environmental experience to improve those designs. (While not rapid on a human time-scale, these changes were often very rapid on a geological time-scale.) Likewise, if one energy technology can undergo many generations of development in the time it takes to build one prototype for another technology, the former is likely to achieve efficient designs sooner and at much lower risk of failure. The latter may reach commercialization only by so compressing its development sequence that the design of each scaling-up must be frozen before operating experience has been gained with its predecessor (as with reactor and synfuel programs).

Accessibility to a wide variety of contributors to this design process--a signal feature of many small renewable sources--further speeds up evolution. Many of the best ideas in renewable energy technologies are coming today from people with little or no technical background. We recently received a letter, for example, from a homesteader in a remote part of Alaska--a man with at best a grade-school education--who had invented some novel and useful solar and wind systems to meet his own needs. On discovering that his biogas digester would handle normal organic wastes but disliked paper, he noticed a moose eating a willow tree, seeded his digester with moose gut, and reported that his digester would now happily digest paper and even sizeable chunks of wood. Thus he has found something quite important, even though he is not Exxon.

Social compatibility--a happy relationship between the technical and social systems--is also important to resilience. For example, an energy system which equitably allocates energy and its social costs to the same people at the same time, so they can decide for themselves how much is enough, is less likely to become embroiled in "energy wars" than a centralized, inequitable system (page 26). An energy system whose impacts are understandable, directly sensible (rather than invisibly threatening), and perceived to be benign and controllable is more likely to be socially acceptable than one lacking these qualities. Technical properties, then, strongly affect the ease of democratic implementation. As Hoover remarks [1979:24], an energy system should be "socially stable," requiring "a minimum of social control. It should not be necessary to deploy force to protect [it]....The system should be able to survive and recover from periods of political breakdown, civil unrest, war and acts of terrorism. The system should be unlikely to become a target of protest; should enhance, not threaten social stability." It should defuse, not generate, tensions and inequities. For greatest efficiency and adaptability in deployment, some observers

would argue that it should ideally be propagated more by networks than by inflexible hierarchies, as the former appear to be a more quickly responding form of social organization [Gerlach 1979].

4.5. Analogous universes.

We have already referred to certain design examples from such areas as civil aviation, military hardware, nuclear reactors, and telecommunications systems. Our readings and discussions in these and other technical areas have revealed that only a handful of people seek consciously to apply such design principles as we have just summarized. Far more commonly, if resilience is achieved, it is by accident in the pursuit of other goals. Design philosophy is normally centered around satisfying narrowly conceived regulations (for, say, reactors) or performance/cost/time specifications rather than producing an inherently resilient product. Even the electric utilities that have thought most deeply about resilience agree that such resilience as their grids possess is a side-effect of other design considerations (e.g. against earthquakes), not "designed in." Military hardware is normally designed only to cope with specific operational threats that can be foreseen and quantified, not with unforeseeable ones, and resilience, if achieved at all, is purely accidental. In both civil and military hardware, efforts to increase resilience are only (as one Pentagon analyst put it) a "hysterical realization after the fact"--that is, design precautions taken against the previous failure. Indeed, those precautions are often applied only to future designs, not retrofitted, because of cost and inconvenience (or pure inertia: the NRC is currently fining TVA \$50,000 for still not having taken basic fire precautions at Browns Ferry, six years after its near-disastrous fire).

Are there technical fields in which the need for resilience^{has} already been so clearly perceived that it has resulted in a coherent, readily identifiable decision to change the architecture of an evolving technical system? Data processing offers such an example, and its lessons have strong parallels to a desirable direction for the evolution of the energy system.

The past decade has seen a wide-ranging professional debate about whether data processing should become more dispersed ("distributed") or more centralized. As microprocessors have packed more performance into cheaper chips--already more complex than human microcircuit designers can handle [Shaffer 1981]--the cost of executing an instruction on a large mainframe computer has come to be equal to or larger than that of doing the same thing on an office microcomputer. But the centralized computers were meanwhile proving disagreeably

"brittle." When they broke down, whole corporations, including time-sensitive ones such as banks and airlines, could be paralyzed. Mainframe computers were harder to understand and repair than small systems. Modifications were painfully slow. Since no "average user" exists, all users were in some degree unhappy with the central computer's match to their own needs. Such forces led Citibank, Bank of America, and a host of other major computer users to seek as dispersed a computer network as they could reasonably achieve. IBM's computer marketing strategy, about a decade ago, was changed to emphasize more dispersed systems that could fail more gracefully. "Distributed processing" is now accepted as the wave of the future--the hottest concept in system design.

A closer look at this history is revealing. One review [Drexhage & Whiting-O'Keefe 1976:1] explains:

During the 1960s, there was a general thrust toward centralizing all the data processing within an organization in the hope that this approach would serve all users. In fact, it did not serve either the central data processing staff or dispersed users as well as was expected...[and attempts at a remedy] resulted in many disappointments as well as some conceptual misdirections in the development of management information systems....

The solution, it now appears, may be decentralization. In the past few years, advances in...technology...have made networks of interconnected minicomputers a plausible alternative to centrally oriented operations. At the same time, pressure from dissatisfied users of central systems has speeded the trend toward decentralization....[Distributed processing meets] an important need for more functionally oriented, more manageable, and more flexible approaches to data processing problems.

The risk of large-scale failure or disruption was on the designers' minds, just as it is now emerging as an issue in energy systems. As some 15 bombings in 10 months blasted French computer facilities [Kessler 1981], the first international symposium on computer security [Murray 1981] heard an American expert "who has so far succeeded in classifying 800 types of computer crime" warn that "within 10 years the real threat to world stability would not be nuclear [war] ...but the ability of one nation to enslave another by paralyzing its computers. ...[In] West Germany,...an operator had succeeded in stealing 22 magnetic bands [disks or tapes] essential for the operation of a large chemical group. The board hesitated only briefly before handing over \$200,000 ransom to recover [them]....Many banks are even more vulnerable....Were a big bank to be affected ...there would be inevitable and serious repercussions on the economy of the country where it was based." In 1979 alone, 633 cases of computer crime were discovered (472 of them in the U.S.), and the current cost of those just in Europe is estimated at over \$3 billion per year. The "average holdup of a computer brings the white-collar criminal a profit of \$500,000 compared with only \$10,000 for the traditional armed holdup." Central computers are vulnerable even to natural disaster: a major California earthquake could make Visa® and Mastercharge® collapse if computing were not restored within a few days.

Another worry is that in a large computer system "it is virtually impossible for a user to control access to his files" and to prevent "subversion of software structures" (i.e. unauthorized alteration of stored programs for purposes of embezzlement, espionage, or extortion) [Lorin 1979:595]. Smaller computers can confine by hardware segregation the amount and sensitivity of information that can be stolen or altered, leading to a major improvement in protection of both corporate interests and individual privacy [Drexhage & Whiting-O'Keefe 1976:5].

Of even more immediate concern to computer users is that

...downtime may balloon to hinder the company's day-to-day operations. For example, one system 'crash' may result in a hour of downtime during which the problem is analyzed; perhaps another hour is lost while operations are restored; and finally, there is an adjustment phase during which time the system again reaches stable on-line operations. All of these delays have significant, and at times disastrous, impacts on corporate operations....

Attempts to minimize this problem have been only marginally successful. ...Large monolithic systems still tend to be unwieldy.

Recent attempts to confront this problem include a new approach to system architecture. New [architectures use]...many processors and memory units interlinked by high-speed communications. All processor units are homologous and capable of replacing each other in case of failure [i.e. they are numerically and/or functionally redundant]. [id.:6]

Lorin [1979:591] identifies similar benefits:

The view that distributed processing can provide greater reliability [data accuracy] or availability [working when wanted] is based upon the economics of replication and the granularity of configurability that interconnected smaller systems may provide. The duplexing or triplexing of small processors...is quite common...[and is attractive because] small...units are inexpensive and additional units give disproportionate reliability increments, while adding modestly to total system cost....The same approach is not equally well applied to large processing nodes because of the larger prices and the incremental jump in total system cost when a large unit is replicated....

Gray [1979:5] summarizes:

[D]ecentralization may have a positive effect on both availability and reliability. In a loosely coupled system, the failure of one system should not affect the other systems. This localization of failures enhances availability. Conversely, by replicating data and programs, systems may act as backup for one another during periods of maintenance and failure. Lastly, decentralization allows for modular growth of the system. When more storage or processing is needed, it may be justified and added in small [and relatively cheap] units.

The key to these benefits--greater security against disruption, equivalent or lower cost of service, more reliable routine operation [Alsberg & Day 1976; Lampport 1978], greater convenience and flexibility to the user--is "node autonomy," the ability of each machine to serve local users in isolation if the communication network fails [Katzman 1977; Bartlett 1977; Highleyman 1980; Gray 1977; Tandem 1981]. Both this design principle and the broader philosophy of which it is a part have striking parallels in the design of resilient systems for supplying energy. We next draw out some of these parallels by examining scale, dispersion, and "granularity" in energy-supplying technologies.

5. SCALE ISSUES

The previous chapters have identified many respects in which gigantic, highly centralized energy systems are inherently vulnerable, and suggested many reasons why more dispersed, diverse, redundant systems should be inherently more resilient. This observation invites two common responses, both incorrect. The first is that contemplating the use of smaller, less centralized energy technologies is really a covert way of seeking to "decentralize society"--to turn cities into agrarian villages, Congress into town meetings, and (by a further emotive extension) modern technology into primitivism. We must immediately disabuse the reader of such a notion. Throughout our published analyses we have been concerned only, as we are here, with how to construct an energy system with maximal economic and national-security benefits. Discussion of what might be the most desirable form of social organization is far beyond our scope here. In point of fact, moreover, neither common sense nor careful study of the actual institutional impact of smaller energy technologies [Messing *et al.* 1979] supports the contention that smaller energy systems entail less centralized patterns of settlement or governance: such technologies actually preserve a complete range of choice in social and political scale. The confusion arises from sloppy terminology (which Appendix C seeks to clarify) and from some advocates' failure to distinguish technical conclusions from political preferences.

The second common reaction to pointing out the greater resilience of smaller and less centralized energy systems is to allege that although this property is doubtless desirable, such technologies are inordinately costly and slow, and are in any case inadequate to the needs of a modern industrial society. This objection, unlike the first, is in substantial part a technical dispute that can be settled on technical merits. We therefore seek in this chapter to consider the economic and logistical implications of scale--of the size of individual energy-converting devices--and in Chapter 7 to consider the adequacy and cost of relatively small-scale energy technologies.

5.1. Appropriate scale.

There is no single correct size for energy-converting devices or systems. The optimal size depends on the use. There is no data base anywhere in the world which shows in detail the spectrum of scales and spatial densities of end-use energy needs for a particular region--let alone the thermodynamic qualities of energy required and how those are correlated with scale and density.

In principle, a least-cost energy system cannot be rigorously designed without such data. One cannot determine the best way to do a task without knowing what the task is.

Simple order-of-magnitude estimates nevertheless suggest that the scale of modern power plants, refineries, proposed synfuel plants, etc.--typically 1-10 GWe (10^9 W)--is much larger than the scale of most end-uses. The heating or cooling load of inefficient houses is typically measured in 10^3 W; the energy needs of large industrial plants range from pathological maxima of the order of 10^9 W to normal maxima of the order of 10^8 W. Most end-use devices used in production are clustered in factories or offices using less than about 10^6 W. Most end-use devices important to our daily lives need of the order of 10^1 to 10^3 W and are clustered in living or working units requiring of order 10^3 to 10^5 W. Most production processes of practical interest have long been carried on in units of the order of 10^5 W or less. Is this enormous mismatch between many supply technologies and most end-uses actually economically advantageous?

Doctrinaire belief in economies of scale has long dominated energy investment decisions. It made the capacity of the largest turbogenerators double "every 6.5 years through five orders of magnitude" [Marchetti 1975]; this tended to increase physical centralization, since total grid capacity doubled slightly more slowly (about every 7 years until the 1970s). The U.S. energy industries, and especially electric utilities, are currently investing tens of billions of dollars per year in facilities of 10^9 -W scale on the assumption that net economies of large scale are real and significant. Yet that assumption has astonishingly sparse support from up-to-date empirical data. Official studies seem to observe almost a taboo on testing dogma against data. Many studies which were supposed to assess diseconomies of scale largely ignored them [e.g. Asbury & Webb 1979; Economic Regulatory Administration 1981], even though the second of those studies supposedly responded to a legal mandate (Public Utility Regulatory Policies Act of 1978, §209) to assess "cost effectiveness of small versus large generation, centralized versus decentralized generation, and intermittent generation, to achieve desired levels of reliability."

This chapter begins to remedy that omission by identifying many types of diseconomies of large scale which most economic assessments of energy systems fail to include. We shall show that in today's economic circumstances, and with a wider awareness of what is economically relevant, "many of the advantages claimed for large scale [in energy systems] may be doubtful, illusory, tautological, or outweighed by less tangible and less quantifiable but perhaps more important disadvantages and diseconomies" [Lovins 1977:86].

In principle, an optimal scale for a particular application could be calculated by superimposing all known economies and diseconomies of scale and finding the minimum-cost point or points (there may well be more than one). In practice, no theory is available for optimizing unit scale with respect to all these properties. Nobody knows what the composite cost-vs.-scale curve would look like in any particular case. Many neglected diseconomies are clearly so large, however, that just a few of them would often suffice to reverse traditional scale economies.

To make this tangled subject tractable, we must exclude from our analysis such questions as the appropriate organizational scale of energy systems. It is important for some purposes, for example, to know that of the roughly 3500 U.S. electric utilities, the largest 10 own about 25% of the total capacity, the largest 30 own 50%, and the largest 100 own 80% [Economic Regulatory Administration 1980:Ex.Sum.8]. (The concentration before the Depression was even greater: eight holding companies produced 75% of the electricity in 1932, although several then went bankrupt as sales declined [Congressional Research Service 1979:11].) But although the scale and nature of utility ownership undoubtedly affect utility economics somehow, we shall not try to determine how. We shall also largely ignore sociopolitical effects of scale in energy systems (some of which we listed in Chapter 2.1), because while they are undoubtedly important--some would say dominant--in the way the United States actually makes public policy decisions about energy, nobody knows how to quantify them.

Our analysis must also be understood in its historical context. We are not arguing that decisions to build large plants in the past were always nonsensical; rather that they would no longer be economically rational in today's quite different circumstances. Nor are we denying that there are often real economies of scale in construction costs per kW installed; only pointing out that this is a gross, not a net, economy, and must be tempered by other effects which at large scale may restrict the energy delivered from each installed kW. That is, any analysis which supposes the objective is to install capacity rather than to deliver energy services is fundamentally misconceived. Finally, because electrical supply has in recent years accounted for two-thirds or more of the capital invested in the U.S. energy sector and in Federal energy R&D, and because better data on scale effects are available for electric than for other energy systems, our examples will be mainly electrical, even though this form of energy accounts for only 12% of U.S. delivered energy and for 8% of current U.S. delivered energy needs. Similar arguments apply to other energy forms.

Ever since the world's first central power station was commissioned in 1882 at Appleton, Wisconsin, the scale of electrical generating and transmis-

sion components has grown with remarkable consistency, leading to real economies in total generation cost (Figure 5.1). The largest generating unit, at first 0.0075 MWe for the earliest pressure-staging turbines [Messing et al. 1979:3], was 5 MWe by 1903, 200 MWe by 1930, and then, after a plateau of more than 25 years, rose rapidly to about 1300 MWe by the late 1970s--though it is far from clear, as we shall note below, that the increase from 200 MWe was economically worthwhile. Maximum steam pressures rose from 2000 psi in the 1940s to over 5000 psi by the 1960s, then fell back to about 2400 psi as it became "clear that some of these technological trends had been extrapolated prematurely" [id.]. Another kind of increased scale was the trend towards multiple units at one site: "while the average size of generating units increased from 22 MWe in 1938 to 30 MWe in 1947 and 49 MWe in 1957, multiple siting...led to increases in average powerplant sizes from 26 MWe in 1938 to 35 MWe in 1947 and 96 MWe in 1957" [id.:17]. Maximum transmission voltages also rose more or less exponentially during the hundred-year history of central electrification, from a few kV to 230 kV during the 1930s, 345 kV by the late 1950s, 500 kV in the early 1960s, and 765 kV in the late 1960s (although megavolt-range lines are encountering such difficulties that 765 kV may represent a saturation level). The increased voltage offered, at least at first, considerable economies, since electricity "can be transmitted over a 765-kV line for 300 miles as effectively as over a 138-kV line for 10 miles" [Congressional Research Service 1979:12]. This trend significantly promoted concentration of utility ownership.

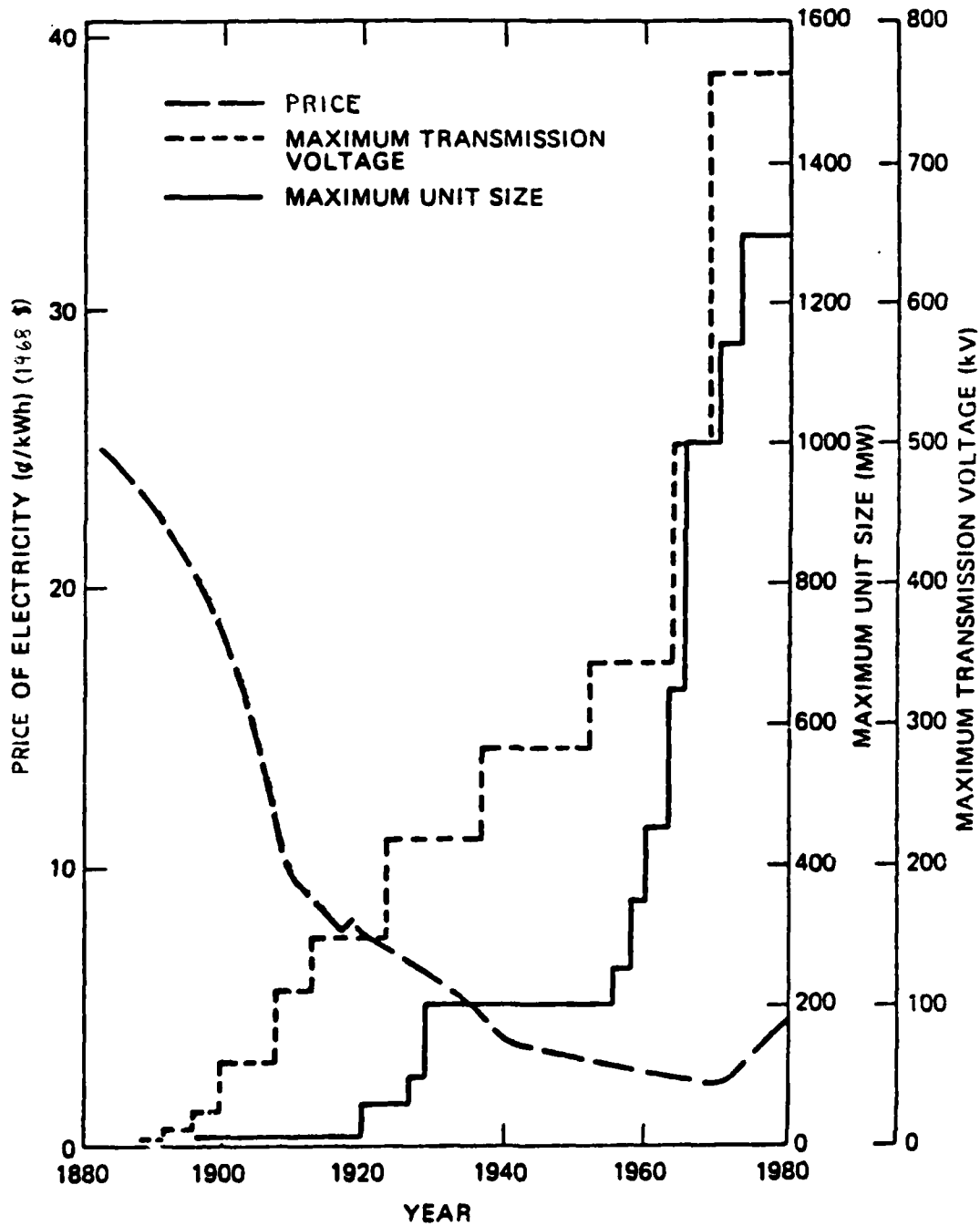
Were these increases of scale economically justified? We next enumerate the effects that were considered, and those that were not but should have been.

5.2. Diseconomies of large scale.

5.2.1. Direct construction costs.

Claimed economies of scale in direct construction costs are dominated by the relationship between variable and fixed costs and by geometrical relationships, e.g. that the cost of building a vessel depends mainly on its surface area, while its capacity depends mainly on its volume, which rises more steeply with size. For this reason, a classical rule of thumb holds that for chemical plants, power stations, etc., cost per unit of capacity tends to rise only as approximately the 0.6 power of plant size [Comtois 1977], so that doubled capacity increases total cost by only 52%. But in practice the savings are mostly exhausted by the time a power plant is as big as 100 MWe, and are trivial or negative above a few hundred MWe [Huethner 1973; Messing et al. 1979:204-206].

Figure 5.1: Evolution in U.S. central-electric technology (maximum generator size and maximum transmission voltage) and in average delivered electricity price (1968 \$) [Economic Regulatory Administration 1981:Fig.2.1].



Several reasons for this departure from the industry's expectations can be readily identified. First, a quarter or more of the total construction cost of large projects is the interest paid on construction capital before commissioning, and "economy of scale is nonexistent in interest rates" [Comtois 1977:52]: bankers charge the same interest rate on a large loan as a smaller one, so as interest becomes a larger component of total construction cost, the scaling exponent of total cost should rise toward 0.7-0.8 or more. Longer construction times, considered separately below, intensify this effect both by increasing interest payments and by decreasing expected economies of scale.

Second, large plants may "involve more complexity, greater precision, smaller margins of error, and new engineering problems" compared to smaller plants [Messing et al. 1979:206]. Thus the shift from subcritical to supercritical steam conditions made the engineering requirements on coal plants far more stringent. Larger nuclear plants lost convective cooling capacity and developed new potential accident modes not characteristic of small plants, requiring new safety analyses and devices. Larger facilities also tend to need more on-site fabrication, which is costlier and more prone to error than prefabrication of subsystems that can be transported whole to the site. And large plants may require "custom design and custom construction. In these cases," remarks the former Chairman of Con Ed [Messing et al. 1979:206], "a consequent increase in the 80 percent of the plant costs represented by field labor and overhead--most of which are time dependent--make[s] the total cost of a larger plant comparable to an equivalent number of smaller facilities," i.e. eliminates net economies of scale.

Third, large units must be more or less custom-built, and cannot benefit significantly from economies of mass production. In contrast, with smaller units "it becomes possible to standardize a design and replicate a large number of identical units." According to a senior official of the [U.S.] General Electric Company, "this opens up the possibility of a new dimension in scale economy" which "may be of considerable significance" [Fisher 1979:10]. The saving from mass production can so outweigh traditional scale economies in construction that the optimal turbogenerator size would be the smallest, not the largest, that can be made for specified steam conditions, opening up "an entirely new and profoundly different avenue for reducing the capital cost of generating capacity." [id.:12] Thanks to mass production, car engines cost only a few dollars per kW of shaftpower, while the engines that drive power stations cost hundreds of dollars per kW. Car engines could be made as durable as power-station prime movers at an extra cost very much smaller than their initial cost difference, leaving at least a tenfold saving from mass production.

The combined result of these phenomena (except perhaps for mass production, which is seldom relevant at the large unit sizes considered) is illustrated by an exhaustive statistical analysis of the entire body of U.S. experience with commercial coal and nuclear power stations [Komanoff 1981]. For nuclear plants, the scale exponent is not 0.6 as hoped but rather 0.904--that is, doubling the plant size reduces the direct construction cost per installed kWe by only 13%, not by the 20-30% assumed in all industry and government cost analyses. (The very existence of the decline is also statistically less certain than for most cost variables.) As will be mentioned below, construction time also increases with unit size, and the extra interest costs decrease the 13% saving per kW with doubled capacity to only 10%--two or three times less than is normally assumed [id.:200]. For coal plants, although it is normally presumed that doubled size reduces cost per kWe by 10-15%, there is in fact no statistically significant correlation between size and cost: at most, there might be (at only 82% statistical significance) a gross cost saving of 3%, reduced to only 2% net by the longer construction time [id.:220].

5.2.2. Operating costs.

Although no detailed data are yet available on operating and maintenance costs as a function of unit size, it is clear from operating experience with all kinds of power stations that larger ones tend to have more numerous and complex failure modes, longer downtime, more difficult repairs, higher training and equipment costs for maintenance, higher carrying charges on spare-parts inventories, and higher unit costs of spare parts made in smaller production runs. Fisher [1979:10] notes more simply that there "may be a reduction in maintenance personnel for smaller units because of their higher reliability" (discussed further below). Large units may be more able to afford and equip the specialized maintenance cadres they require, but become correspondingly more vulnerable to those cadres' whims, as noted in Chapter 2.1.11.

The repair problems of large industrial plants generally have been surveyed by Petzinger [1981]. High interest rates have "made it more important than ever to keep plants operating," and the "high cost of financing inventories has forced manufacturers to live within tight production schedules: any equipment breakdown is bound to anger customers and likely to cost a company business. Yet while costly money has increased the pressure to avoid breakdowns, it has also made them more likely. Many companies believe they are forced to cut corners when building new plants, either by eliminating backup equipment or going without spare capacity. 'It used to be that you'd install a

spare pump at every critical point in a refinery. You can't afford to do that willy-nilly now,' says [a senior officer of a construction firm]....Moreover, neither equipment manufacturers nor their customers can afford to keep a wide range of spare parts in stock. This is due not only to the high cost of financing the parts, but also to the cost of the parts themselves. Westinghouse Electric Corp. has managed to sell about 100 spare power-plant turbine-rotors in the past five years by persuading utilities that they can save seven days of costly outage by having parts on hand. But for many utilities the cost of these spares, currently \$1 million to \$7 million, is prohibitive." Simply installing them is a risky and demanding operation: "We're dealing with things that are extremely heavy and yet extremely delicate," said a Con Ed official.

Since smaller plants are normally simpler, lower skills and standards of maintenance may suffice; the plants are more comprehensible to their staff; and they are more likely, in a technical sense, to fail slowly and gracefully. All the extra costs of maintenance for larger plants then operate in reverse. It may be true that it is simpler to arrange delivery of fuel, or conversion from one fuel to another, for a single large plant than for multiple smaller plants; but this argument is irrelevant to comparisons between conventional power stations and renewable energy sources, which depend on a energy flux that is freely distributed and [stochastically] assured.

5.2.3. Availability.

A low cost per kW of installed capacity is useless if that capacity is not available to provide energy. The reliability of large power stations has in fact been generally discouraging. As Robert Mauro of the American Public Power Association remarked [Messing et al. 1979:209], "the disappointing availability record of many large units has diminished, if not entirely dissipated [,] the theoretical savings expected from bigness....[It is ironic that] many small...electric utilities, which have been jeered at for operating 'obsolete' plants with 'tea-kettles,' have had fewer problems in maintaining adequate power supply than some larger systems with modern large-scale units." Komanoff [1981] has quantified these effects. The capacity factor (actual output as a fraction of full-time full-power output) of all commercial U.S. power reactors through June 1980 averaged 66% for the 23 plants (173 plant-years) under 800 MWe, but only 54% for the 39 plants (188 plant-years) over 800 MWe. Sufficient experience is available, according to the industry, to distinguish statistically the effects of age from those of size. The correlation of the 12-percentage-point gap with size is now unmistakable [id.:248]. The inverse correlation of

availability with size is equally striking for coal plants [id.:253-257]: during 1961-73, average unit size increased from 226 to 400 MWe while capacity performance (a measure of availability) fell from 79.6% to 69.3%. Coal plants in the size range 400-800 MWe were about 8 percentage points less available than 200-400-MWe ones. For all coal and oil plants, 1967-76, the forced outage rate (fraction of the time the plant was broken down) ranged [Ford & Flaim 1979:35] from 2.5% for plants <100 MWe to 16.1% for >799 MWe, rising more and more steeply with increasing size in between [Anson 1977]. It is partly for this reason that the average size of newly installed coal plants fell from about 700 MWe in 1971 to 440 MWe in 1978; 300 MWe is now a common size.

Similar experience abounds worldwide. As the Federal Energy Administration was castigating the dismal reliability of large new power plants in the U.S. [Weekly Energy Report 1975], similar evidence was already accepted in Europe as indicating a fundamental mistake had been made in investment strategy. A German/British conference in 1973, for example, had already found that poor availability had cancelled expected economies of scale in coal plants. The larger plants took longer to "mature"--to overcome their "teething troubles"--and never did become as reliable as smaller units: after four years' operation, availabilities ranged from about 82% for 60-MWe units (which had levelled off at their "mature" availability) to only about 52% for 500-MWe units, which were still far from maturity. Intermediate sizes fitted into this correlation correspondingly.

The reasons for the correlation are simple and fundamental. A 500-MWe boiler has approximately ten times as many miles of tubing as a 50-MWe boiler, so "a tenfold improvement in quality control is necessary to maintain an equivalent standard of availability for the larger unit" [Electrical Times 1973]. A more complex control system encounters the discouraging mathematics of multiplicative component-failure probabilities (pages 150-151). A large turbine has correspondingly high blade-root stress*, often forcing the designer to use exotic alloys with unexpected characteristics: highly skilled turbine designers in several advanced industrial nations have watched their turbines explode because the metal did not behave as hoped. The technological evolution required to meet ever more stringent performance standards exhibits diminishing returns to money and talent invested: any technology which tries to sustain a short doubling time indefinitely will come unstuck sooner or later. Scaling up rapidly often outruns engineering experience (especially in long-lead-time technologies). Detailed assessments of reactor component reliability--pumps, valves, etc.--show lower reliability at larger scale [Procaccia 1975; see also Knox 1977]. Since about 80% of the cost of sending out a unit of electricity

*The same effect (plus vibration) makes megawatt-range wind machines complex and costly. No net economies of scale have been demonstrated above 20-50 kWp.

from a nuclear plant is its capital cost (or about half that much for coal plants), electricity price, even after the cost of delivery is added, is strongly sensitive to reliability.

5.2.4. Thermal efficiency.

Power-plant engineers have devoted immense ingenuity to trying to increase the amount of electricity derived from each unit of fuel. By the 1960s, average thermal efficiencies had been improved from <23% to about 34%. But in recent years, average plant efficiency has slightly decreased. This is partly because larger plants, built in the hope of wringing another few tenths of a percentage point out of the thermal inefficiency, proved less reliable [Electrical World 1975]. Their frequent stopping and starting greatly increased heat losses and entailed more part-loaded operation at reduced efficiency. Thus in Britain, for example, among stations of the same size (500 MWe), thermal efficiency ranged from 23-24% for plants with 5-10% capacity factor to 34-35% for plants with >60% capacity factor [Electrical Times 1973]. For all plants >449 MWe, the correlation was equally strong [Abdulkarim & Lucas 1977:226]; the adoption of a standard size of 500 MWe instead of the optimal size of 200-300 MWe (based only on availability, thermal efficiency, maintenance cost, lead time, and direct capital cost as functions of size) led to a 16% overbuilding of U.K. generating capacity. In the U.S., the ten most efficient power plants operated in 1974 (with heat rates around 8800-9200 BTU/kWe-h or thermal efficiencies around 37-39%) ranged in size from 238 to 950 MWe and in vintage from 1958 to 1970; the larger or newer units were on the whole no more efficient than the older and smaller ones [Messing et al. 1979:10,14]*.

5.2.5. System integration.

The thermal efficiency of a power plant is inadequately measured by its conversion of fuel only into electricity, because this process inevitably loses about two-thirds of the fuel's energy in the form of low-temperature heat which is normally wasted. By capturing this heat and using it to heat buildings or greenhouses via a combined-heat-and-power station and district heating, the thermal efficiency of converting the fuel into useful work can be raised to 80% or more. This can also be done on the scale of a neighborhood or building with great economic savings [Hein 1979]. Alternatively, if electricity is made in a factory as a byproduct of high-temperature heat or steam already being made there, this "cogenerated" electricity [Williams 1978] can cost about half as

*Efficiency (and energy cost) are likewise uncorrelated with unit scale or centralization in most solar-thermal technologies [OTA 1978 ; Caputo 1977].

much, and use about half as much fuel, as would result from making the same amounts of electricity and process heat in separate installations. It is not hard to estimate, as a general illustration, that if an electrical generating system is losing two-thirds of its fuel input as waste heat, as is approximately the case nationally, and if (conservatively) two-thirds of that otherwise wasted energy can be recaptured, then if the heat displaces that from a 70%-efficient furnace fired with \$36/bbl OPEC oil, each kW-h of electricity will receive a waste-heat credit worth 4.3¢--more than the entire cost of generating an average kW-h in the U.S. today. The cost of the apparatus to capture and use the heat will be a small fraction of this value.

Ability to take advantage of such opportunities for integration depends on unit scale. A 1-GWe power station produces about 2 GWt of warm water--far too much to use conveniently. The largest readily manageable combined-heat-and-power systems operating in Sweden (a leader in this technology) are half this size, serving the heat and power needs of a city of about 100,000, but the district heating system took 17 years to build up. Sizes of tens of MWe down to tens of kWe or less (for apartment buildings) are far more tractable.

Similar integration opportunities exist for sharing infrastructure, cost, inputs, and outputs between energy systems and buildings, food and water systems, etc. Such opportunities are greatest with renewable energy sources, as Chapter 7 will illustrate further.

5.2.6. Transmission and distribution costs.

Large-scale energy sources are mismatched to the scale of most energy uses. For U.S. private electric utilities in 1965-71, for example, the average power density of final demand was of the order of 0.030 W/m^2 , ranging an order of magnitude higher or lower in extreme cases. The density for nonindustrial users was only half this great (p. 27)--an exceedingly low density, about 1/12,000 that of sunlight. A 1-GWe plant with a load density of 0.030 W/m^2 will serve a territory with a radius of about 150 km. (The average distance electricity is transmitted from new plants of all sizes, including many around 1 GWe, is actually about 350 km in the U.S.--100 km in the denser European grid--partly to benefit from load diversity, the fact that different uses occur at different times, so a given amount of capacity can be shared among more demands than it could meet simultaneously. This is an economy of scale of the grid, not of its power stations.) Thus large power stations provide enormous amounts of energy from a small site, but energy uses tend to be dispersed over a very large area.

This mismatch between supply density and load density entails a costly transmission and distribution network. In 1972, the last year for which a detailed analysis is available, the cost of building and maintaining that grid

accounted for about 70% of the cost of delivered U.S. electricity [Baughman & Bottaro 1976]--more than twice the cost of generation. (Similarly, transmission and distribution accounted for 65% of delivered residential gas prices in 1976, and wellhead gas for only 29% [AGA 1977].) In recent years, these ratios have probably shifted: U.S. electric utilities spent about 73% of their 1979 investment on generation, 10% for transmission, and 13% for distribution, compared with 50%, 19%, and 28% respectively in 1969 [Economic Regulatory Administration 1980:Exec.Summ.:9]. But since the grid also loses about a tenth of the electricity sent through it, and since the cost of operating and maintaining the grid is probably greater than the capital charge for transmission [Baughman & Bottaro 1976], even this marginal cost breakdown suggests that about a third of the price of marginal delivered electricity is for delivering it, not for generating it. This is a significant diseconomy in the large scale of generators. Both costs and losses could be greatly reduced by better matching of scale to end uses--the same strategy that can reduce vulnerability.

Some estimates of the "dispersion credit" that smaller generating units can provide by saving transmission and distribution investment have been published. A recent survey of five such studies using widely varying assumptions [Systems Control 1980:Summ.:43-44] found credits ranging from \$8 to \$165 per kW of dispersed generating capacity. None of these studies allowed credit for displacing underground cables, which constitute the majority of new primary distribution circuits and can cost 10-40 times as much as overhead circuits. Several of the studies did, however, include credit for increased reliability of service to the end-users. This arises because a source at the distribution substation, or even closer to end-users, protects them from transmission failures--the dominant cause of all supply failures--and may thus improve reliability by a factor of ten or even twenty. (To procure the greatest benefit, the dispersed source should be as close to the user as possible, since an estimated 85-95% of all customer outages are due to failures in distribution, not in the bulk generation/transmission system [*id.*:Rpt.:5.47; Systems Control 1980:3-7; *cf.* Economic Regulatory Administration 1981:4-10].)

5.2.7. Reserve margin.

The unreliability of large units is worse than appears at first sight, because the possibility that a large unit might fail requires the provision of an equally large block of backup capacity to protect the grid. Conversely, a larger number of smaller units provides partial protection because they are not all likely to fail at the same time [Ouwens 1977] and hence would need less

reserve margin to achieve the same reliability. "The enhanced reliability contribution of small generating units arises because the failure of a single large unit is more likely than the simultaneous failure of two smaller units equalling the same capacity." [Economic Regulatory Administration 1981:7-4f] For this reason, several studies of typical interconnected grids [e.g. Kahn 1977; Wisconsin PSC 1977] show that building several power plants of 300-400 MWe, rather than a single 1000-MWe plant, would provide the same level and reliability of service with about a third less new capacity. Thus 1 GWe of nuclear capacity at the margin should, in such a grid, be compared in costs and impacts with perhaps 0.7 GWe of coal plants because the latter can come in smaller units. For still smaller units, such as 10-MWe fuel cells sited at distribution substations, the savings in extra capacity to do the same task may exceed 60% [Peschon 1976] because of the added protection from grid failures. (This saving diminishes as more dispersed sources are added to a standard grid.)

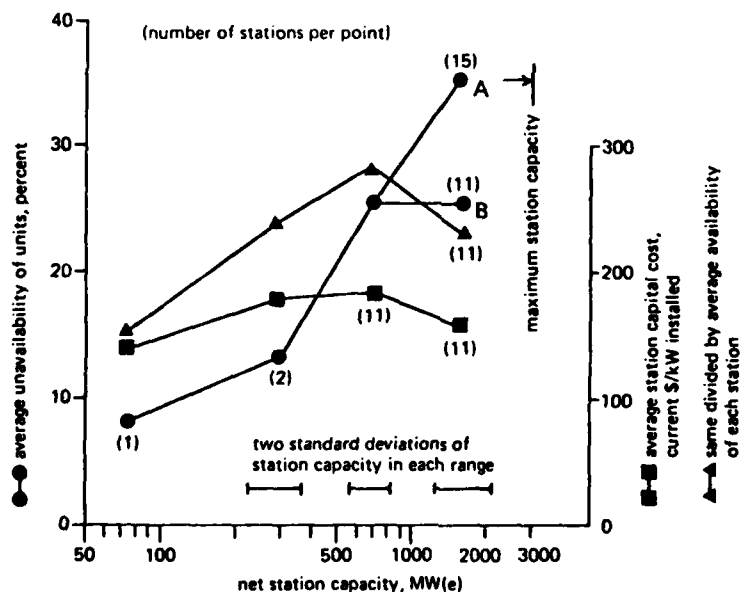
Another illustration of the saving in reserve capacity is offered by a calculation by Peschon et al. [personal communication, 1978]. For a loss-of-load probability of one day in ten years (the normal U.S. standard) and a forced outage rate of 4%, generating units with a size sufficient to supply 2% of the peak load require reserves of only 5% of the peak load; units providing 10% of peak load require about an 11% reserve; units providing 20% need about 23%; units providing 50% need about 65%. That is, the reserve requirements rise steeply with bigger, "lumpier" units. For a 15% forced outage rate, the reserve requirements at these unit sizes are respectively about 22%, 43%, 62%, and 150%: that is, the reserve requirements are greatly accentuated by the unreliability of the units. The reserve requirements rise even more steeply in grids that are not interconnected [Galloway & Kirchmayer 1958].

A detailed analysis by Ford & Flaim [1979] used empirical cost and performance data to compare two patterns of building coal-fired power plants: four of 750 MWe or nine of 250 MWe. The larger plants would need require a third greater total capacity to do the same job because they are less reliable and can "drop out" more capacity at once. The smaller plants' 25% capacity savings, 19% (11 percentage points) higher capacity factor, ca. 44% shorter construction time (5 years instead of 9), and 59% (8.1 percentage points) lower forced outage rate make up for their 15% worse thermal efficiency, 11% higher capital cost/kW, and slightly higher costs for coal transportation and electricity transmission. When all these effects are balanced, the total cost (discounted to present value) of building the smaller plants is less by 1% in operation, 17% in construction, and 6.1% in lifetime electricity price--a total saving of \$227 million (1977 \$) compared to the larger plants [id.; Ford 1979]. Many other potential cost savings, such as district-heating potential or reduced cost of money from the more favorable construction cash flow, were not included in this analysis.

5.2.8. Construction time and indirect costs.

As cost of money and escalation of real capital cost take a larger share of total construction costs, due to the interrelated increase of capital intensity, scale, technical complexity, perceived impacts [Komanoff 1981], and lead times, total economies of scale decline [Comtois 1977]. There is some evidence that for very large units, economies of scale in capital cost per installed kWe actually become negative. Figure 5.2, for example, shows the capital cost per installed kWe (squares) or per kWe available to be sent out (triangles) as a function of unit size. The sample is half of the thermal power stations commissioned in the U.S. in a two-year period during 1972-74 [Electrical World 1975; Lovins 1977:92]*. Remarkably, capital cost per installed kWe in this sample is less for a small station than for a very large one.

Figure 5.2: Average unavailability and specific capital cost vs. unit size in a nearly even-aged sample of 29 thermal power stations.



*The sample includes 17-18 coal-fired, 2-4 nuclear, 3 gas-fired, 2 gas- or oil-fired, and 1-2 oil-fired stations--a total of 29 in every region except New England. Point A is from the original source's graph, point B from its supposedly corresponding tabular data; their difference apparently reflects very high unavailability in the four very large stations included in the graph but whose availability figures are omitted from the table. The right-hand triangular point is calculated with the lower value (B). Komanoff's [1981] smallest reactor is 457 MWe, so his positive economy of scale is consistent with the graph.

A possible explanation for this unexpected result arises from differences in construction times as a function of scale. Although it might seem intuitively that doubling the size of a plant will double its construction time, utilities have traditionally expected any increase in construction time to be negligible. Komanoff, however, finds [1981:208-209,224] that doubling the size of a nuclear or coal plant actually increases its construction time by 28% or 13% respectively, simply because of the sheer volume of materials and labor whose use must be coordinated. (These increases refer only to actual construction time, not to licensing. Komanoff [1981:205], like Mooz [1978,1979], found no statistically significant correlation between licensing duration and reactor cost.) Ford & Flaim [1979], who also consider the process of siting and licensing, find even stronger scale effects on construction time. The Federal Power Commission reported that during 1967-76, utilities cited vendor-related problems (late delivery, unacceptable quality, etc.) as being responsible for 37% of their plant delays, poor site labor productivity and other labor-related problems for 34%, regulatory problems for 13%, utility-related problems (chiefly finance) for 9%, and bad weather, legal challenges, and all other causes for 8% [Messing *et al.* 1979:207]. The complexity of large projects increases vulnerability to all these problems.

Longer construction times increase the indirect costs of construction in at least seven ways, some of which are difficult to quantify. First, longer lead time increases exposure to real cost escalation [Komanoff 1981]. Second, it increases the absolute and fractional burden of interest during construction [Comtois 1977]. Third, it makes the utility's cash flow less favorable, reduces the self-financing ratio, increases the debt/equity ratio, reduces the interest coverage ratios, and generally increases the utility's financial risk and hence its cost of money in the capital marketplace [Kahn & Schutz 1978; Wiegner 1977]. Fourth, it increases the project's exposure to regulatory changes during construction [Komanoff 1981] and to technological progress that can alter the design criteria or even make the project obsolete. Fifth, it may increase the incentive (and bargaining power) of some construction unions to demand very high wages, or to stretch out construction still further, or both (as occurred on the Trans-Alaska Pipeline). Sixth, large plant scale increases the transaction costs of siting [Ford & Flaim 1979] because its impacts are more obtrusive. (This may lead utilities to try to maximize installed capacity per site, making the project so big and problematical that the plant becomes a worse neighbor than it should have been, so the next site becomes that much more difficult to find, and so on exponentially.) Seventh, long lead time exposes the builders to high financial risk because of uncertainty. This problem deserves explanation.

"[T]he greater time lags required in planning [and building] giant plants mean that forecasts [of demand for them] have to be made further ahead, with correspondingly greater uncertainty; therefore the level of spare capacity to be installed to achieve a specified level of security of supply must also increase." [Cantley 1979] Longer lead time increases both the uncertainty of demand forecasts and the penalty per unit of uncertainty. Some analysts [Cazalet et al. 1978; Stover et al. 1978] have attempted to show that the penalty for underbuilding is greater than the penalty for overbuilding; but their recommendations --to overbuild baseload plants--are artifacts of flaws in their models [Ford 1978; Ford & Yabroff 1978; Lovins 1981]. More sophisticated simulations [Ford & Yabroff 1978; Ford 1978, 1979a; Boyd & Thompson 1978] show on the contrary that (at least for utilities which do not carry unfinished plants in their rate base) if demand is uncertain, the low-financial-risk strategy is deliberately to underbuild large, long-lead-time plants. There are three reasons for this. The extra carrying charges on unused large plants exceed the extra operating costs on overused short-lead-time stopgap plants (even gas turbines); short-lead-time plants have a shorter forecasting horizon and hence greater certainty of being needed; and short-lead-time plants can be built modularly in smaller blocks, responding more closely to short-term perceptions of need. These qualities all reduce the financial risk and therefore the utility's cost of money [Kahn 1978:333f; Lovins 1981; Appendix A].

5.2.9. Control of residuals.

It is often claimed that centralization simplifies control of residuals, such as air pollutants released by burning coal. But there are many counter-arguments. Smaller scale may reduce the total load of residuals by permitting the use of combined-heat-and-power plants or of more flexible and inherently benign processes (for example, fluidized-bed combustion of coal, now commercially available in sizes of tens or even hundreds of MWt but not of GWt). Smaller scale lowers both the risk and the cost of failure in individual pollution-control installations: less will get out than in the case of failure at a large plant, and there is less fiscal incentive to bypass a defective scrubber than if the alternative were shutting down a major power station). Smaller scale, by siting the plant near its users, also gives them a direct incentive to insist that it run cleanly and quietly. For example [Hein 1979], a combined-heat-and-power plant powering and heating an apartment complex at Heidenheim, West Germany, uses a natural-gas-fired Otto engine built in a garage-like structure. Its acoustic isolation is so effective that its noise cannot be distinguished

from the noise of water running underground in the sewers at midnight. It has to be that quiet--because there is a house a few meters from the exhaust. Since the people who get the energy also get the side-effects themselves, they insist that the project be built right. (The extra cost of the soundproofing is very quickly recovered from the economic savings from using the waste heat.) Conversely, when a large plant is rurally sited, agrarian politicians are often impotent to enforce environmental standards in the face of its overwhelming economic power. The result is often inequity, giving rise to tensions and perhaps to violence [Gerlach 1979; - & Radcliffe 1979; Casper & Wellstone 1981].

5.2.10. Other issues of scale economics.

Large plants may make it easier to use and finance the best technologies currently available. On the other hand, smaller plants with shorter lead times may, at each stage during rapid technological evolution, have less capital sunk in inflexible infrastructure, and may reflect a shorter institutional time-constant for getting and acting on new information. Small plants may be perceived as so benign, and fit so well onto existing sites near users (such as the sites of old municipal power stations), that they have few siting problems: they offer far greater siting flexibility [Fisher 1979:10] than large plants, and this in turn saves transmission costs and losses, increases the scope for total-energy systems, and encourages the use of inherently superior sites.*

A social or psychological perspective suggests many further scale effects. Some, like users' perceptions of dependency or oligopoly, are beyond our scope here [Lovins 1977b]. Others are of a more technical character. For example, large technologies tend to submerge, but small ones to emphasize, individual responsibility and initiative. This may improve the quality of work and decisions. Furthermore, large technologies, as Freeman Dyson has remarked, are "less fun to do and too big to play with." They are so complex and expensive that their design is fixed by committees, not changeable by a single technologist with a better idea. The kind of fundamental innovation which evolved cheaper and more effective energy systems in the past has often depended on the technologies' accessibility to a multitude of tinkerers. (This emerges clearly from the relative speed of innovation in large vs. small wind machines or in mainframe vs. microcomputers.) The ability of a single person to understand a technology and make a basic contribution to it is of fundamental importance: there is, so far as we know, nothing in the universe so powerful as four billion minds wrapping around a problem. It is for this reason that many of the most

*Some instances of siting problems with small units have been reported, however, especially if the local community has not participated in the decision.

exciting solar developments, as noted earlier, are the work of individuals, often without the trappings and inertias of "big science."

Finally, small units, especially with local storage or optional interconnections, can not only increase the resilience of energy supply in the many ways described in previous and subsequent chapters; they can also be far more easily protected, repaired, and replaced or augmented by expedient means. Replacement or augmentation will be discussed further in Chapter 6, and repair in subsequent Chapters. Protection, in a civil-defense sense, can be as simple as placing a device "on shock-absorbing material such as styrofoam blocks, wrapping it in plastic, covering it with crushable material such as plastic chips or metal shavings, and covering this all with a thick layer of dirt." [Joint Committee on Defense Production 1977:11:45] Such measures, adapted from Soviet practice by Boeing for protecting industrial equipment, can protect it from "extremely high blast pressures, and presumably...[from] fires and falling debris." No similar techniques are applicable to large-scale technologies, which are conspicuous, tempting targets, hard to repair, hard to replace, and impossible to shield.

To summarize the economic arguments so far: the economies of scale classically expected in direct construction costs are typically tens of percent (hundreds at extreme sizes). Most of the diseconomies just identified are each of this magnitude. Almost any combination of a few of them could tilt the economic balance (for all but highly concentrated applications) toward small scale. Thus there is a prima facie case that big technologies may not be inherently cheaper, and may well be more expensive, than those scaled to dispersed applications.

Of course, there are tasks for which big systems are appropriate and cost-effective: it would, for example, be just as silly to run a big smelter with little wind machines as to heat houses with a reactor. Mismatching scale in either direction incurs unnecessary costs. What matters, to reemphasize the point, is the right scale for the particular task. But even in our highly industrialized society, nearly all the energy-using devices are smaller--most of them are orders of magnitude smaller--than the GW-scale supply systems that have hitherto been assumed to be economically essential. We have sought to show that a more sophisticated and comprehensive view of the economics of whole energy systems leads to a very different balance of sizes between demand and supply.

5.3. Scale and speed.

The scale of energy technologies affects not only their cost but also their speed of deployment--how much per year, or per dollar invested, they can raise the rate of energy supply. While the forces that determine actual deployment rates are largely political, and their future course is thus somewhat conjectur-

al, there are theoretical grounds for believing, and empirical grounds to confirm, that relatively small technologies are likely to be built faster, in terms of total energy supplied, than conventional large-scale energy technologies--provided that strong obstacles are not deliberately put in their way.

It may at first seem counterintuitive to suggest that doing many small things may be quicker than doing a few big things. It is certainly contrary to the thrust of official energy policy. It seems to be contradicted by one's sense of the tangible importance of a large refinery or power plant. Yet in a deeper sense, the success of the free-market economic philosophy on which American private enterprise has been built depends very directly on the speed and efficiency of many individually small decisions by sovereign consumers. It is precisely because those decisions work faster, better, and more accurately in giving practical effect to private preferences that Americans have opted for a market system--one of decentralized choice and action--rather than for a centrally planned economy on the Soviet model. And in energy policy, this selection has been rewarded; for today those individual decisions in the marketplace--decisions to use energy more efficiently--are, in aggregate, affecting the national energy picture two orders of magnitude faster than all the big supply projects put together. (We shall offer data to this effect below.)

Despite this success, many energy planners are reluctant to rest their confidence in these individual actions--because such actions are not under the planners' direct control as a large construction project is (or is supposed to be). Yet exactly the same mechanisms are at work in individuals' small actions to increase their energy efficiency that have always been invoked as the rationale for forecasting growth in energy demand. The countless small market decisions which collectively constitute national demand are simply responding to a different set of signals than they did previously. The bottom line is the same: numerous small actions by people plugging steam leaks, weatherstripping doors, and buying more efficient cars are adding up to the fastest-growing contribution to national energy supplies.

Our comparison of the speed of actions at different scales will center around two kinds of relatively small-scale technologies: those for increasing the productivity of using energy and for capturing renewable energy flows. We shall describe those technologies' nature, status, and economics in Chapter 6 and in Chapter 7 respectively. (Analogous arguments also apply to fossil-fueled technologies of similar scale, such as fuel cells and cogeneration devices.) But our argument here is really about scale, not hardware, and so should logically precede a fuller development of the details of the devices themselves.

The scale and simplicity of all these devices gives them several advantages which should enable them to provide needed energy services faster, per unit of investment, than larger and more complex alternatives. First, each unit takes days, weeks, or months to install, not a decade. Secondly, those units can diffuse rapidly into a large consumer market--like digital watches, pocket calculators, CB radios, and snowmobiles--rather than requiring a slower process of "technology delivery" to a narrow, specialized, and perhaps "dynamically conservative" utility market (like 1-GWe power plants or basic oxygen furnaces). This is a function of the relative understandability, marketability, and accessibility of the technologies--of their comparative technical and managerial simplicity and how easily they can adapt to local conditions. These factors determine the mechanism and hence the rate of market penetration.

Technologies that can be designed, made, installed, and used by a wide variety and a large number of actors can achieve deployment rates (in terms of total delivered energy) far beyond those predicted by classical market-penetration theories. For illustration, let us imagine two sizes of wind machines: a unit of several MWe peak capacity, which can be bought for perhaps \$1 million and installed by a heavy-engineering contractor in a few months on a specially prepared utility site; and another of a few kWe, which can be bought by a farmer on the Great Plains from Sears or Western Auto, brought home in a pickup truck, put up (with one helper and hand tools) in a day, then plugged into the household circuit and left alone with virtually no maintenance for 20-30 years. (Both these kinds of wind machines are now entering the U.S. market.) Most analysts would emphasize that it takes a thousand small machines to equal the energy output of one big one (actually less, because the small ones, being dispersed, are collectively less likely to be simultaneously becalmed [Kahn 1979; Sørensen 1979].) But it may also be important that the small machines can be produced far faster than the big ones, since they can be made in any vocational school shop, not only in elaborate aerospace facilities, and are also probably cheaper per kW. What may be most important--and is hardly ever captured in this type of comparison--is that there are three orders of magnitude more farms than electric utilities on the Great Plains*, subject to fewer institutional constraints and inertias.

The third reason for suspecting that many small, simple things should be faster to do than a few big, complicated things is that the former are slowed down by diverse, temporary institutional barriers--passive solar by the need to retread architects and builders, microhydro by licensing problems, greenhouses by zoning rules, etc.--which are largely independent of each other. In con-

*Likewise, California has four main utilities but >200,000 rural wind sites with ready capacity >10 kW [Congressional Research Service 1979:113].

trast, large and complicated plants are slowed down by generic constraints everywhere at once, such as major-facility siting problems and large-project financing. Because of their independence, dozens of small, fairly slow-growing investments can add up, by strength of numbers, to very rapid total growth, rather than being held back by universal problems. To stop the big plants takes only one insoluble institutional snag; to stop all the diverse kinds of small plants takes a great many. This diversity of renewable and efficiency options is not only a good insurance policy against technical failure; it also helps to guard against specialized, unforeseen social problems in implementation, offering a prospect of alternative ways to evade what problems do arise.

The theoretical advantages of these smaller technologies are borne out in practical experience. The fastest gains in U.S. energy supply have come from small efficiency-improving technologies. During 1973-78, the U.S. already got twice as much energy-"supplying" capacity from numerous small energy-saving actions, twice as fast, as synfuel advocates say they can provide at ten times the cost (if they are given \$22 billion to get started with)*. In 1979, 98% of U.S. economic growth was fueled by energy savings, only 2% by actual expansions of net energy supply; thus millions of individual actions in the marketplace, by people trying to save energy to save money, outpaced the centrally planned, long-lead-time supply projects by better than fifty to one. In 1980, while real GNP stayed constant within better than 0.1%, total U.S. energy use dropped by 3.2%. (Danes decreased their direct fuel use by 20% just in the two years 1979-80, largely through better thermal insulation of buildings.)

This trend is accelerating. Americans spent some \$8.7 billion on small energy-saving devices in 1980 and are expected to spend tens of billions of dollars per year by the mid-1980s [Business Week 1981]. Sant et al. [1981] have shown that \$100 billion per year would be economically worthwhile. Supply industries, used to the far slower progress to which their complex technologies with ten-year lead times have confined them, have been caught unprepared by the efficiency boom, and many utilities and oil companies are now suffering financial hardship as sales unexpectedly decline. (There are some silver linings, however: some of Royal Dutch-Shell's most profitable subsidiaries sell energy-saving and -managing services. This is proving an extremely high-return enterprise: one such firm, started in 1979, expects \$250 million turnover in 1983.)

Small-scale renewable sources are--after efficiency improvements--the second-fastest-growing part of U.S. energy supply [RTM 1981]. During 1977-80, renewables gave America 1.2 quads of new primary energy while the total contribution from nonrenewables fell by 0.6 quads [id.]. A few illustrations:

*Likewise in the EEC, increased energy efficiency in 1973-78 supplied more than ten times as much new energy capacity as increased nuclear power. The ratio of energy savings to net supply increases was 95:5 [St. Geours 1979]. Japan has had an average growth rate of 4%/y in real GNP since 1974, yet at the same time has experienced essentially zero growth in total energy use.

- The U.S., which already gets over 7% of its primary energy from renewables (mainly hydroelectricity) [RTM 1981], now has about half a million solar buildings, of which half are passive and half those are retrofits (mainly greenhouses, plus some glazing of exterior masonry walls to form Trombe walls). Many of these were built on the basis of word-of-mouth or popular-journal information, few from officially provided information. In the most solar-conscious areas, about 6-7% of all space heating is solar, and 25-100% of the new housing starts are passive solar designs. Nationally, about 15% of the contractors building tract houses, and virtually all purveyors of prefabricated and package-planned houses, now offer thermally efficient, passive solar designs.

- In New England, over 150 factories have switched from oil to wood, as have more than half the households in many rural (and some suburban) areas. Private woodburning has increased more than sixfold in the past few years, and the number of stove foundries has risen from a handful to more than 400. Private and industrial woodburning in 1980 supplied the U.S. with about twice as much delivered energy as nuclear power did [Lovins & Lovins 1981:66n144].

- There are over 40 main wind-machine companies. Commercial windfarms are competing on utility grids, and more are being rapidly built (pp. 246-7).

- Some 10-20 GWe of small hydro capacity is under reconstruction (mainly refurbishing old, abandoned dams). A further 20 GWe at 2000 sites awaited permits in mid-1980 [Ron Corso, FERC, personal communication, 4 August 1981]--twice the gross nuclear capacity ordered since 1975. Companies to build microhydro or resell power to utilities are springing up [Siegel 1981](p. 245).

- There are over a thousand retail outlets for Gasohol®, and most states have biomass fuel programs.

In short, it is hard to find a part of the U.S. that does not have its unique blend of renewable energy ferment. Many observers who travel the country remark that although these activities are concealed from governments' view by their dispersion, small individual scale, and diversity, they add up to a quiet energy revolution that is reshaping the American energy system--like the Japanese* [Tsuchiya 1981]--with unprecedented speed.

From the vantage point of the five years or so in which this revolution has been well underway, it may seem that the results are meager. But so it must have seemed in 1900 when there were about 5000-8000 cars on U.S. roads, or even in 1908 when there were 194,000. Cars became more noticeable in 1911 when the 600,000 on the roads caused Standard Oil to sell for the first time more gasoline than kerosene. Two years later there were a million cars; seventeen years after that, in 1930, 23 million; today, over 100 million. In the first decade after World War I, the automobile became sufficiently widespread to

*Japan's primary energy is 7.2% renewable (cf. 8% officially forecast for 1995) including 0.8% direct solar, with >\$500 million worth of collectors (750,000 for water heating, 13,000 for process heat) sold in 1980 alone.

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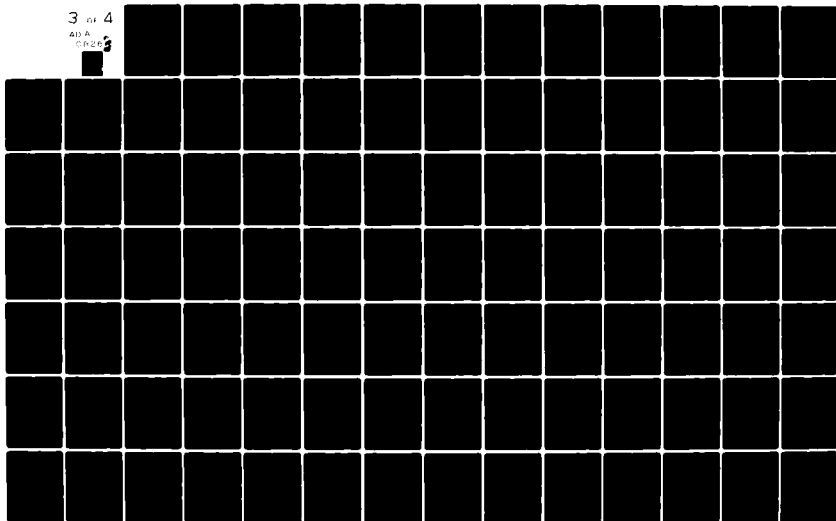
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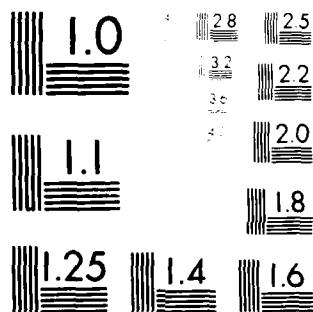
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transform at first the perceptions of mobility and later, in consequence, the settlement patterns and the whole industrial infrastructure of American society. Yet the car may not at first have seemed so portentous: indeed, on the assumption (common in the early twentieth century) that car drivers would have to pay for their highways just as railroads had had to pay for their railbeds, the odds seemed stacked against the commercial success of the car. Until the Model A and Model T brought cars to every town, few observers expected rapid success. Thus profound changes in the technostucture of America can creep up on us unawares. Small energy technologies--for efficient use and renewable supply--may well be repeating the story.

Nobody can say for sure whether they will ultimately work such a transformation. But they certainly have the technical, economic, and social potential to do so. As the Office of Technology Assessment concluded [1978]:

If energy can be produced from on-site solar energy systems at competitive prices, the increasing centralization which has characterized the equipment and institutions associated with energy industries for the past 30 years could be drastically altered; basic patterns of energy consumption and production could be changed; energy-producing equipment could be owned by many types of organizations and even individual homeowners. Given the increasing fraction of U.S. industrial assets which are being invested in energy industries, tendencies toward centralization of many aspects of society could also be affected.

As we shall see in subsequent Chapters, small technologies for energy efficiency and renewable supply already meet the test of "competitive prices." Even in 1979, before many further improvements had persuaded such institutions as the Southern California Edison Company to pursue aggressively an efficiency/renewables strategy as the cheapest option, a distinguished panel found [Aspen Institute for Humanistic Studies 1979:Summ.2] that "Decentralized [electricity] generation systems are likely to confer major consumer benefits. These may include shorter lead times in planning and construction, easier siting, reduced capital requirements, greater efficiency in fuel use, and reduced vulnerability to fuel shortages....We find a number of such options are at, or are approaching, a state of technical and economic competitiveness with larger centralized systems." The panel also found that "On balance,...the climate for the development of small, diversified, and dispersed supply and [efficiency]...options is likely to improve." Small, whether beautiful or not, is at least serious.

For these reasons, it now appears to many analysts that a fundamental shift in the architecture of America's energy system may be underway, with profoundly encouraging implications for resilience and national security. We explore next the most important element of that transformation: the dramatic and continuing increase in national energy efficiency.

6. END-USE EFFICIENCY: MOST RESILIENCE PER DOLLAR

Although concerns about energy vulnerability are usually stated in terms of interruptions of energy supply, e.g. oil imports or electrical deliveries, what is really of concern is not the protection of energy supplies but rather of the tasks that the energy performs after it is delivered. There is no demand for energy per se. Raw kilowatt-hours, or barrels of sticky black goo, are not a useful commodity. Energy is not an end in itself but only a means of providing energy services--comfort, mobility, light, ability to make steel or bake bread. If a given service can be provided with no energy--as a house can be space-conditioned passively if it is built properly--then for that task, there is no energy supply to be interrupted, hence no energy vulnerability. In a more typical case, some energy is required to provide a desired service, but the amount of energy is not fixed: it can be reduced by increasing the end-use efficiency of the service, so that the same service is performed, with unchanged reliability and convenience, using less energy. Thus it is not true that the more energy we use, the better off we are. The optimum is rather to use the amount (and the type and source) of energy that will provide each desired service in the cheapest way.

Improving energy efficiency may require extra investment in money, brains, or attention. From an economic point of view, one must decide how much investment to wring more work out of one's energy will be cheaper than investments to provide additional energy supplies. This balance may not coincide, however, with that dictated by vulnerability concerns, because measures to increase end-use efficiency will in general be less vulnerable than measures to increase supply. Roof insulation and heat exchangers simply cannot be disrupted in the same way as oil tankers and transmission lines. Moreover, as we shall show, efficiency improvements often reduce the end-user's vulnerability to disruption of the remaining energy supplies, even though they are only reduced in quantity, not changed in source. For these reasons, including the social cost of vulnerability will tend to tilt the optimal balance away from new supply and toward efficiency. As a conservatism, however, this discussion will consider only the narrow economic viewpoint of direct (private internal) costs, and will confine itself to those efficiency improvements which cost less than corresponding increases in energy supply. Most of the improvements we consider are also cost-effective at present energy prices, which "roll in" costly new supplies with cheaper old supplies and thus understate the "marginal" cost of increasing supplies. Thus our economic comparisons, by counting only direct costs, impli-

citly value all risks, vulnerabilities, and side-effects at zero. By pursuing least economic cost, however, we shall fortuitously achieve major improvements in energy resilience.

Many energy preparedness planners are unused to dealing with energy efficiency. Their day-to-day concern is the other way of "saving" energy--doing without it and hence curtailing the services it provides. Efficiency gains are commonly considered to be a gradual, long-term process that is the task of energy policy; in this view, if an energy shortage does strike, it is too late for anything but belt-tightening. Emergency energy planning thus tends to focus on allocating scarce supplies in a spot shortage so that critical, high-priority needs can still be met--if still at low levels of energy efficiency.

We consider here the opposite approach: seeking to reduce or eliminate the risk of shortages by increasing end-use efficiency, in advance of any shortage, to levels which provide a generous "cushion" of both normal and emergency energy supplies. By doing more with less, it may be possible to avoid having to do without. Insulating the roof may avoid freezing in the dark.

Improving end-use efficiency offers, we shall argue, the best buy in energy resilience--to paraphrase an old Pentagon slogan, the "most bounce per buck." Its benefits arise at all scales, from that of the individual user to that of a nation or the world. These benefits are multiple, synergistic (the total benefit is greater than the sum of its parts), and nonlinear (small improvements buy a disproportionate amount of insurance). To explore them, we begin with a brief survey of available, cost-effective measures to raise end-use efficiency.

6.1. The state of the art.

Improvements in U.S. energy efficiency in the past eight years have been remarkable. They were largely responsible for decreasing net U.S. imports of oil (crude oil plus refined products) from 9.0 million barrels per day in 1977 to 8.7 in 1978, 8.4 in 1979, 6.0 in 1980, and about 5.4 in mid-1981--well below the 6.3 of 1973. A group of oil industry leaders forecast in 1980 that, contrary to their expectations in 1978, total U.S. demand for refined products will probably stay about constant through the 1980s [Los Angeles Times 1980], with demand for gasoline, home heating oil, and residual fuel oil actually falling. So far events have improved on those projections. In California --which uses over 10% of all U.S. gasoline--there were nearly a million more cars in 1980, driven almost 10 billion vehicle-miles further, than in 1976, yet gasoline use in 1980 was the lowest since 1976 [Billiter 1981a; Los Angeles

Times 1981j]. For the entire U.S., gasoline demand in March 1981 was the lowest in ten years. Declining total oil demand became the rule, not the exception--so it was news when, in January 1981, unusually cold weather led to the first increase in national oil use in two years [Los Angeles Times 1981k].

These figures are encouraging, but they do not instantly reveal their cause. Such aggregated figures as net oil imports lump together domestic demand with domestic oil extraction and interfuel substitution. Aggregated demand data cannot distinguish between changes in the energy intensity of providing the same services and changes in the composition of services provided (since some, like smelting, need far more energy than others, such as banking); between changes in efficiency and changes in total economic activity; between improved efficiency and degradation of energy services (e.g. reduced comfort in buildings); and between better progress in some sectors (notably industry) and worse progress in others. Such aggregated measures as energy/GNP ratios or levels of net oil imports are thus not suitable for comparing energy efficiencies over time or between countries. These measures cannot reveal either how much end-use efficiency has been improved or how much improvement is still possible and worthwhile. For those purposes, the only practical approach is to assess "technical coefficients"--how much energy is used, in physical units, to provide a precisely specified unit of each energy service.

In the past few years, a large international literature has assessed what these coefficients currently are and what they can, with economic advantage, be changed to under a wide range of conditions. These data can be transferred from one place to another if careful attention is paid to differences of climates, of preferences in the size and performance of cars, in the different kinds of ore fed into steel mills, etc. The technical literature on practically achievable efficiency gains is so vast and so fast-moving that it would not be feasible in a study of this length to summarize even all its main results. We have attempted this elsewhere, most recently in a study originally commissioned by the West German government [Lovins, Lovins, Krause, & Bach 1981]. Two authoritative analyses based almost entirely on the U.S. literature [Sant et al. 1981; SERI 1981] have reached similar conclusions in even greater detail. For present purposes, however, it is sufficient to survey typical developments in just a few key sectors. Those not treated here in detail are analogous.

6.1.1. Buildings.

The 80 million dwellings in the United States, using altogether about 35% of all U.S. primary energy demand, were mainly built before 1970, when real

energy prices were low and falling lower, giving no incentive to build efficiently. During the 1970s, under the spur of air-conditioning bills that sometimes exceeded mortgage payments and annual household energy costs which, in New England, trebled from \$386 in 1970 to \$1325 in 1980 [Washington Post 1981a], the average thermal efficiency of American houses was improved by at least 15%. But by 1978, the houses still required about 13 BTU of fuel (compared to 16 in 1970) to heat one square foot of floorspace through one Fahrenheit degree-day of outdoor coldness (13 BTU/ft²-DDF is about 265 kJ/m²-DDC) [Rosenfeld et al. 1980]. (This assumes a 70%-efficient furnace. Actual furnace efficiencies are often lower, but this should be dealt with separately from the thermal efficiency of the house itself.)

The state of the art in cost-effectively efficient houses, however, is ten to a hundred times better than that: it is not 13 but 0-1.3 BTU/ft²-DDF. This can be achieved by various combinations of "superinsulated" tight construction and passive solar gain (capturing and storing solar heat, even on cloudy days, in the fabric of the house itself, e.g. through south-facing windows). (We do not consider here other techniques, such as double-envelope or earth-tempered construction, for achieving the same aim.) "Superinsulated" houses in a cold climate typically have about a foot of insulation in the walls (say R-40), two feet in the roof (R-60), double or triple glazing, insulated night shutters, and virtually airtight construction, with plenty of fresh air provided by mechanical ventilation through a simple air-to-air heat exchanger, which can recover about 80% of the heat or coolth in the outgoing air. These techniques reduce the gross heat loss through the shell of the house so far that the internal heat gains--from windows, occupants, lights, and appliances--provide most or all of the space heating. Such supplementary heat as may be needed in an especially unfavorable climate is so small--much smaller than the heat needed for domestic hot water--that it can be provided by slightly increasing the south window area, taking surplus heat from a slightly oversized solar water-heater, burning a newspaper or a few sticks in a small stove on rare occasion, or keeping one or two 40-watt poodles. Such houses have lower life-cycle cost (and often lower construction cost) than normal houses, look the same, can be built in any style, provide a higher standard of comfort than normal houses--less noise, less dirt, no drafts, excellent temperature stability--and do not, if properly designed, require any significant changes in the occupants' behavior.

The examples most often cited for such construction are the Saskatchewan Conservation House (considered in more detail below)--and its hundreds of successors in Canada and the U.S.--and the Illinois Lo-Cal design. Both types

are being routinely built by tract-housing contractors; the governments of Canada, Saskatchewan, and Alberta have spread the necessary building information so effectively [University of Saskatchewan 1979] that there should be over a thousand such houses finished by the end of 1982, even though the first one was finished only in December 1977. The Saskatchewan design had in 1980 a net additional capital cost of 7-8% (about US\$2600 or less), paying back in about four years against the present OPEC oil price--and the price was falling in real terms as contractors gained experience. The net extra capital cost of the Lo-Cal design was at most about \$1000, and in some houses, e.g. those of Phelps and Leger, it was reportedly zero or negative: the saving from not having to install a furnace more than paid for the additional insulation, etc.

[Rosenfeld et al. 1980; Shurcliff 1980; Leger & Dutt 1979; Shick 1980]. The measured net space-heating fuel requirements to maintain comfort in these houses are respectively 0.8 BTU/ft²-DDF for the Saskatchewan Conservation House, 1.1 for Phelps, and 1.3 for Leger [Rosenfeld et al. 1980]. These figures are not only 10-16 times better than the U.S. average (13); they are also better than any present or proposed U.S. building standard. The widely used ASHRAE 90-75 code yields about 10.7 BTU/ft²-DDF; the HUD 1974 Minimum Property Standard, about 9.6; typical 1976-79 U.S. building practice, about 6.8; the Building Energy Performance Standard (BEPS) proposed in 1979, about 4.4; and a proposed "strict BEPS," about 2.3. No BEPS standard has been enacted or is being actively considered at present, even though houses exceeding its "strict" version would probably cost less to build than normal houses.

Although these highly efficient designs have most of their window area facing more or less south, and little or none on the north side, they are not really intended to be good passive solar designs. With proper passive solar techniques which are no costlier than superinsulation and may be cheaper, the levels of insulation needed for similar or better performance can be considerably relaxed. The right combination of thermal efficiency and passive solar gain can reduce net space-heating requirements to essentially zero (<0.1 BTU/ft²-DDF) in climates worse than that of Chicago [SERI 1981:I:31], at a total extra capital cost of at most about \$2000--paying back in <4 years at the 1981 OPEC oil price or in <2 years at the 1981 average residential electricity price. An added benefit of many passive solar designs is a "sunspace"--extended living space that is bright and comfortable even on cloudy winter days, and in which fresh food can be grown year-round in severe climates. The optimal balance between superinsulation and passive design is normally rather broad, and depends on local climate, construction practice, and architectural taste.

The same measures that reduce heating loads also reduce air-conditioning loads by not letting the house get hot in the first place. Additional measures include window shades and overhangs and coatings, trees, roof ponds, and earth-pipe cooling (a cheap, effective form of passive air conditioning). And the energy savings are not confined to space heating and cooling. A combination of water-efficient appliances and recovery of waste heat from outgoing "graywater" (from dishwashing, washing machines, showers, etc., but not including sewage) can generally cut the water-heating load in half [Carter & Flower 1981]. Most if not all of these measures are cost-effective at the present world oil price, and all are cost-effective against electrical or synfuel prices.

Intelligent redesign of household appliances can reduce their average use of electricity by three- to four-fold [Nørgård 1979, 1979a] with an average payback time under 6 years at the present average U.S. residential electricity price--all with no change in performance or convenience. An average U.S. frost-free refrigerator, for example, uses about 1700 kW-h/y; Amana has a 675-kW-h/y prototype; the best 1981 Japanese models use about 400 (for the same size); under 200 is cost-effective today.

The efficiency improvements that can be made in space heating and cooling, water heating, lights, and appliances are often even larger and cheaper in the commercial sector (offices, hotels, churches, schools, hospitals, etc.) than in houses. Many office buildings were designed to be cooled and heated simultaneously, and most of their cooling load is to take away the heat of overlighting (i.e. at headache level). Just the difference in lighting intensity between offices built in the early 1970s (about 4 W/ft²) and in 1980 (2 W/ft²) would by 2000 eliminate the need for 150 1-GWe power plants [SERI 1981:I:54-55]. The average U.S. office building in 1978 used over 340,000 BTU of total resource energy, as direct fuels plus power-plant fuels, to space-condition, light, and otherwise operate a square foot of floorspace. Hydro Place, a glass utility headquarters in Toronto, uses 170,000; Gulf Canada Square in Calgary, about 117,000; the best office buildings now nearing completion in Canada, 20-30,000. All these designs have payback times of a few years.

So far we have described only new buildings. But most of the buildings that the United States will have over the next half-century are already standing, so the main focus must be on retrofitting (fixing up) those existing stocks. Extensive data are available [SERI 1981; Carhart *et al.* 1980] on the empirical cost and performance of retrofits. Most of the techniques described above can be applied, with minor modifications, to existing buildings. Some Canadian builders remove the siding from a frame house, build out the eaves and casings, add a vapor barrier and superinsulation, and put the siding back on,

cost-effectively cutting the space-heating load by 90% or more. Where this operation was combined with adding extensions to houses, it could be done for only about C\$3000--less than the cost of enlarging the furnace [Palmiter & Miller 1979]. Ingenious techniques for retrofit have been developed for a wide range of construction styles. It is common in Europe even to add exterior insulation and a new façade on masonry walls, trapping their large heat-storing capacity or "thermal mass" inside and so stabilizing the building temperature. Even elaborate measures of this kind, in countries (such as Sweden and FR Germany) which have the world's highest labor costs, specific costs of retrofit several times U.S. levels, and relatively efficient buildings to start with, are cost-effective at present OPEC oil prices [Lovins, Lovins, Krause, & Bach 1981:25]. In well-planned programs, retrofits to tighten and insulate U.S. houses or commercial buildings have cost about \$1/ft² of floorspace, or about \$6-7/bbl (15¢/gal) of equivalent oil savings [SERI 1981:24-27,65]. This cost applies for savings of more than two-thirds of the original average energy use. Even suboptimal programs--such as those which plug only visible air leaks in houses rather than pressure-testing to find hidden leaks, or which use storm windows rather than insulating shades and other cost-effective window treatments--cost about \$19/bbl (40¢/gal) [SERI 1981:I:27]--still highly competitive with OPEC crude oil at \$34/bbl, synfuel at \$40-80/bbl (1979-\$ plant-gate price assuming \$34/bbl oil price) [Congressional Research Service 1981], or electricity at \$90-120/"bbl" of heat content.

6.1.2. Transportation.

Two-thirds of America's transportation energy, and over half of all U.S. oil use, goes to cars. The cars average about 16 miles per U.S. gallon (mpg), the light trucks nearer 12. Technical improvements in the engine and drive train, lubricants, tires, streamlining, and bearings can improve these figures to 80-110 mpg for a 4-passenger car of about the same size and performance as the average 1981 domestic model [SERI 1981; Gray & von Hippel 1981; TRW 1979; Shackson & Leach 1980]. The total cost of improvements to 60 mpg is \$800-2260 per car [Shackson & Leach 1980; Gorman & Heitner 1980; SERI 1981], corresponding to a payback time, at the present gasoline price, between one year and three and a half years.

Some manufacturers are already well on the way to these goals. A VW diesel Rabbit™ already averages about 40 mpg on the road; average 1981-model Japanese cars get 42-45 mpg on the road; VW has prototyped a turbocharged diesel Rabbit™ which has a 60 mpg EPA composite rating, meets all emission standards,

accelerates 0-60 mph in 13.5 seconds, and is safe in a 40-mph head-on crash [VW of America 1980]. Most impressively, an advanced VW diesel prototype with a Rabbit™ body and a 3-cylinder engine which turns off on idle or coast, then immediately restarts on acceleration--a car for which VW had claimed on-road composite efficiency of 80 mpg [Seiffert & Walzer 1980]--was recently tested by the EPA at 80 mpg city, 100 mpg highway. (On-road mileage in real driving cycles will probably average over 80 mpg.) Even these empirical achievements do not exhaust the possibilities offered by series hybrid drives, infinitely variable transmissions (being introduced in 1981-82 by Borg-Warner/Fiat), etc.

It is important to note that these 60-90 mpg achievements do not even consider another option--using cars more specialized for their tasks, notably 2-seater commuter cars for the vast majority of personal driving. Such cars are selling well in many other countries [Boyle 1981; Lehner 1980; Japan Automotive News 1980], especially the Japanese "mini-cars," measuring no bigger than 4.5 by 10.5 feet and displacing no more than 550 cc, but currently capturing over 20% of the domestic market in highly urbanized Japan. Their attraction is that some models get on-road efficiencies of 53 mpg city, 75 highway. (In contrast, GM's newly announced diesel Chevette gets only 40/55 mpg.) Such designs offer a good match to the urban driving needs of many Americans, and with modern crushable-foam materials, can be safer than conventional cars. Mixing commuter mini-cars into the fleet could send fleet averages over 100 mpg.

Straightforward application of proven and cost-effective technology can reduce the specific energy requirements of heavy trucks and buses by 30-40% and of railroads by about 25%. New Japanese ship designs have cost-effectively saved about 50% of normal fuel requirements. Commercial aircraft (7% of U.S. transportation fuel use) have improved their fleet efficiency from 17.5 passenger miles per gallon in 1973 to 25 today and will reach 45 once the new generation of aircraft has been fully introduced (Boeing 757 and 767, DC9-80, and advanced L-1011)--a 45% improvement in fuel efficiency. Even larger savings are available from new technologies for turbofan engines, special propeller and wing designs, active control technologies, and weight-saving materials; together these promise a saving of about 70%.

6.1.3. Industry [SERI 1981; Sant et al. 1981; Lovins et al. 1981].

The ten most energy-intensive U.S. industries during 1972-79 decreased their energy consumption per unit of product by an average of 15.4% [Energy Insider 1981]--almost entirely by measures paying back within one or two years at the then current rolled-in fuel prices. The efficiency of using process

heat (about 43% of all industrial energy) rose by about 4% per year. But there is still cost-effective scope for saving at least a third more heat by better thermal insulation, heat recovery, process controls, heat pumps, cogeneration, and use of best available processes. Alumina smelters can likewise save at least a third of their electrical input by adopting superior processes (Alcoa, Pechiney). Proper sizing, coupling, and controls would save about half of the electricity needs for industrial motors (27% of all industrial primary energy use); this one improvement, typically paying back in a few years, would more than displace every nuclear power plant in the country. Innovative industrial processes even more efficient than we have just stated are being rapidly developed, such as a new process which saves over three-quarters of the energy needed to make ethylene. A substantial fraction of industrial energy can also be saved by more efficient use, recycling, and remanufacturing of materials.

Whether efficiency in each sector is improved all the way to these cost-effective levels or only partway, the improvement benefits energy resilience at the scale of both the user and the whole society. We consider these in turn.

6.2. Micro benefits.

Increased end-use efficiency decreases the vulnerability of energy users, at the scale of an individual household, office, shop, or factory, in four main ways: longer time constants, limiting extreme behavior, shaving peak loads, and displacing marginal supplies. (The last of these can be considered a micro or a macro effect or both, so this section inevitably overlaps somewhat with the following one.)

The concept of making failures happen more slowly in order to give more time in which to respond is familiar in preparedness planning. It is the strategy of a person who puts containers of water in the freezer as a "thermal flywheel" so that in a power failure, the freezer temperature will rise only slowly and cannot exceed the freezing point until all the ice has melted. It is the strategy of a smelting company that insulates its potlines to slow down their heat loss, so that if the electric current that keeps the alumina and cryolite molten is only briefly interrupted, they will remain molten. (The alternative--months of work chipping them out with chisels--is so unpleasant that it is worth buying a lot of insulation.) It is the strategy of stockpiling, but improved: an energy system which uses oil more slowly to provide the same energy services is better than one which uses more oil but draws down a stockpile in case of supply interruption, because while the stockpile costs

money to maintain and finance, the more efficient energy system saves money all the time, whether there is an interruption or not.

Let us consider a very localized, specific example of lengthening time constants: a superinsulated house [Besant et al. 1978; Dumont et al. 1978]. The Saskatchewan Conservation House is in Regina at 60.5° N. latitude in a fierce climate--10,800 DDF/y, a design temperature (expected extreme cold) of -29°F, and average insolation of 162 W/m² (about 10% less than the U.S. average). It is a two-story frame box with 2000 ft² of floorspace, R-40 walls (offset double two-by-fours), R-60 roof, a tight 6-mil vapor barrier with infiltration less than 5% air change per hour, an 80%-efficient air-to-air heat exchanger averaging 0.6 air changes per hour (more can be provided if desired), double glazing downstairs, triple glazing upstairs, insulated night shutters, an air-lock entrance, and insulated door and foundation slab. As a result of these highly cost-effective measures, the total heat loss through the shell of the house is only 38 watts per F° of temperature difference between inside and outside when the window shutters are closed (55 with them open, 45 average). The gross shell loss totals only 41.2 million BTU/y. But after allowance for the "free heat" from windows, people, lights, and appliances, the net space heating load is only 5 million BTU (1400 kW-h)/y--less than 4% as big as for an ordinary Regina house the same size*. Furthermore, the superinsulated house has a solar system big enough to cover all of its space and water heating needs, using no backup; yet that solar system contains only 190 ft² of collectors (9.5% of the floor area) and 15.3 yd³ (3090 gal) of water storage (2.8% of the house volume). Most studies would predict that five to ten times this area and volume would be necessary to cover even two-thirds of the space- and water-heating load. How, then, can the smaller system be big enough?

It is in answering this question that we see how profoundly the efficiency improvements have altered the basic physics of the house. An ordinary house requires sharp peaks of heat to maintain its inside temperature whenever the weather turns cold. These peaks often exceed 10 kW even in a mild California climate [Kahn 1979:316], and in an ordinary Regina house they would be many tens of kW, requiring either a large furnace or (with electric heating) installed generation, transmission, and distribution capacity costing about as much as the house itself. In contrast, the Saskatchewan Conservation House holds in its heat so effectively that even with a 99 F° temperature difference across the shell--+70°F inside and -29°F outside--the interior temperature can be maintained with only 3.7 kW of total heat supply if the shutters are closed or 5.5 kW if they are open. Thus the superinsulation and the air-to-air heat exchanger have reduced the space-heating load from a series of huge peaks to a

*Besant et al. [1979] report 12.5 MMBTU [Rosenfeld et al. 1980] in 1978-79, due to air leakage around the shutters and the net heat loss from ca. 1000 visitors/wk, but expect to return to "about 5" with "some further work."

series of small blips superimposed on a water-heating baseload. The average heat requirement is three times as big for heating domestic water as for heating the whole house, even though the water-heating load has itself been reduced by a third by recovering heat from graywater. To cover the greatly truncated peaks of space-heating, far less collector area and storage volume is needed.

Secondly, although the house has "low thermal mass"--it can store heat only in its light frame construction, so its heat capacity is only 23,700 BTU/F°--its "time constant" (the time it would take for the inside to fall 63.2% of the way to the outside temperature if no heat were provided from any source) is about 100 hours, or about four times as long as for a normal house of similar construction. The Saskatchewan Conservation House stores no more heat, but loses it far more slowly. For delaying the drop in temperature, this is exactly equivalent. Such a house provides inherent protection, because if its heating system fails, a spell of cold weather is likely to have moderated before the inside temperature drops far. For example, in 0°F weather, the house would take 34 hours to drop to 50°F in total darkness. Under the conditions least favorable for passive solar gain through the windows--averaging 787 W in December--the house would probably take several weeks to get as low as 50°F, and temperatures much below that would be physically impossible unless the tightness of the house were somehow seriously damaged. Thus if the house had no working furnace, baseboard heaters, solar collector, or any other external heat source, an occupant willing to tolerate an English rather than an affluent North American standard of comfort (say 55-60°F in cold weather) could go right through the Canadian winter without even realizing there was no heating system.

This behavior illustrates both the stretched time-constant of the house--everything happens in slow motion--and its inherent limitation of extreme behavior. Any properly built passive solar house cannot get below about 50-55°F no matter what. Even a badly built passive solar greenhouse, provided it has a reasonable amount of thermal mass (rocks, masonry, drums of water, etc.) for overnight heat storage, will never get below freezing, even in a Minnesota climate. So robust are structures of this kind that in one Massachusetts passive building, when vandals broke down the door and left a hole of 2-3 yd² through the coldest night of the winter, the interior temperature still stayed above 60°F. (That building did not have insulating night shades, which would have stretched its time constant from days to weeks.) It is also noteworthy that the Saskatchewan house's heat-storage tank, spanning its full 90 F° temperature range, would supply space and water heating at the annual average rate, with no heat input, for 48 days--just like having a full 3000-gallon oil tank in a normal house, or a tenth of the normal inventory of a heating-oil

distributor [Congressional Research Service 1977:I:248]. A gallon of the hot water stores only 0.5% as much energy as a gallon of oil, but serves about equally well because so much less energy is required to do the same task.

A third important result of the Saskatchewan Conservation House's superinsulation is that heat can only diffuse inside the house--it can scarcely get out. The inside of the house is in almost perfect convective and radiative equilibrium. Thus any point source of heat, such as one short section of uninsulated hot-water pipe, can heat the whole house evenly without requiring a heat distribution system. In this way an Alaskan superinsulated house can be evenly heated by a tiny stove putting out a few hundred watts in one corner, yet have uniform temperatures within about a degree even to its furthest corner, far away around labyrinthine corridors. This means that if normal heating fails, a superinsulated house can be heated amply by any small, improvised heat source--a small wood- or trash-burner, a camping stove, a small lantern. The heat thus provided will provide comfort throughout the house, whereas in a normal house with a failed heating system one would have to huddle over a large stove to try to keep a single room habitably warm.

In short, the efficiency of this model house (quite aside from its use of solar energy) makes its occupants virtually invulnerable to heating failures. Their neighbors, who would be in serious trouble in a fraction of a winter day without heat, can take shelter in the efficient house and by doing so can provide enough body warmth to heat the whole house. If there are more than one or two neighbors, excess heat will have to be vented by opening the windows! If the failure affected the heating sources of all houses, the occupants of the superinsulated house might find out only from the arrival of their chilled neighbors that anything was wrong; left to their own devices, they would probably not notice for weeks that their heating system was out of order, and then the signal would be a drop from 68-72°C to perhaps 55-60°F, not a catastrophic drop to sub-freezing or subzero temperatures indoors. As in the Aachen house in Germany (four times less efficient, yet physically incapable in an average-weather year of getting below 55°F inside with no space heating whatever), the occupants of such a house would be all but invulnerable to energy disruptions.

Long time constants are not always a blessing. A Swedish superinsulated house took about two years to attain its design efficiency because its building materials had been left outdoors and wetted by rain. The house needed so little heating that it took that long to dry out the materials. Likewise, a large seasonal-storage tank for a community district heating system could easily take a year to "charge up" to normal working temperatures--though once heated, it would "coast" indefinitely thereafter. Thus long-time-constant

energy systems must be in place before an energy shortage strikes. But if working then, they are likely to outlast the shortage and vastly increase the flexibility of possible responses.

The ability of either well-insulated buildings with some passive gain or badly insulated buildings with strong passive gain to protect under all circumstances against low (especially sub-freezing) temperatures means that activities such as greenhouse gardening can be guaranteed to work year-round anywhere south of the Arctic Circle. Year-round passive-solar greenhouse gardening, even using tropical species, has proven highly successful even in parts of the U.S. that have a three-month growing season outdoors. Another advantage is that even a very crude, unglazed solar water heater--such as a piece of blackened sheet-metal attached to a hot-water pipe--can work well inside such a greenhouse. Being always protected from freezing by the thermal mass and solar gain relationships of the greenhouse, the solar water heater needs none of the anti-frost precautions (draindown valves, double antifreeze loops with heat exchangers, etc.) which can make conventional outdoor solar water heaters relatively complex and expensive.

6.3. Macro benefits.

The foregoing examples have shown how a more thermally efficient house can reduce its occupants' vulnerability by lengthening time constants, preventing extremes of temperature, and making small, improvised sources much simpler, more flexible, and more effective. But the house is only a microcosm for the entire American energy system.

A 60-mpg car, for example, can be driven four times as many miles or days as a standard car on the same amount of fuel. It can therefore canvas a considerably larger area in search of fuel, or be four times as likely to stay on the road long enough for improvised supplies of liquid fuel to be arranged*. Stockpiles of all kinds last four times as long, yet this fourfold expansion effectively incurs negative extra carrying charges because of the cash-flow of the cars' fuel saving in normal operation.

An efficient car "frees up" three such cars' worth of fuel; that is, given some constrained amount of available fuel, four times as many car-miles can be

*Its engine may also be more suitable than most for using unconventional fuels, as mentioned in Chapter 7: the Boat Division of Chalmers in Sweden has even reportedly burned wood flour successfully in large diesels. Given adequate lubrication, diesels tend to be less particular about their fuel than ordinary Otto-cycle engines.

driven if the cars get 60 mpg as if they get 15. Visits to the filling station become four times as infrequent. The 1.5 billion gallons of fuel stored in vehicles' fuel tanks (61% full) in August 1979 [Energy Information Administration 1981] would constitute a reserve capable of powering a 60-mpg fleet of 130 million cars and light trucks for nearly 700 miles each, or four weeks' driving at the average August 1979 rate. Thus the dynamics of any fuel shortage would be dramatically different than with cars that must be refueled every few days. With such a fleet, mobility would be undiminished even if several major oil pipelines, refineries, and ports suddenly disappeared. Fuel reserves "in the pipeline" between the wellhead and the gas pump would last not for a few months but for a year or more--plenty of time to arrange improvised biomass liquid fuel supplies large enough to run essential services if not virtually the whole fleet (Chapter 7). For the first time, stockpiles "in the pipeline" would last for about as long as it takes to repair major damage to pipelines, ports, etc., so the country could withstand considerable destruction of oil facilities without shortages or the need for interim rationing.

Similar advantages would arise with electricity. Just as a house that is thermally efficient can provide most or all of its needs with "free heat," so one that is electrically efficient can rely only on the most uninterruptable components of supply: local renewables and grid hydroelectricity. Of course, a household (in most U.S. climates) really concerned with saving electricity will have not an electric refrigerator but a seasonal-storage icebox--a superinsulated box which is filled with several yd³ of water each autumn from a garden hose, then allowed to freeze (via a removable panel of insulation) and spend the rest of the year melting out through a drain-hole. Food on the other side of a partition from the large block of ice will not spoil even in a permanent power failure. But even an efficient conventional refrigerator, using a few hundred kW-h/y instead of the present average of 1440, will itself warm up very slowly, because its efficiency derives partly from excellent thermal insulation. The week or more it will keep cool without power offers enough breathing-space to hook up an improvised power supply or direct mechanical drive, using perhaps a car or bicycle. The installed generating capacity of generators and alternators in U.S. cars and trucks is over 100 GWe--a sixth as much as in the entire national grid--and, with present hydroelectricity, would probably be enough to meet all national electrical needs if electricity were used at a cost-effective level of technical efficiency (Appendix A). If the stock of end-use devices were economically efficient, essential household needs--food preservation, lighting, radio [Goen et al. 1970:83]--would average only about 50 W, rather than the present 300-500 W. This tiny power demand could be provided by a car

battery with a small inverter, a tiny improvised wind machine, or a solar-cell array of a few square yards. If the average car battery has a 100-A-h capacity @12 VDC and is kept half-charged, the national fleet's batteries store of order 60 GW-h--enough, after inverter losses, to meet all national electrical demands at current efficiencies for a quarter of an hour, but enough to meet essential household needs at high efficiency for about half a day*. In many communities, an industrial cogenerator or microhydro set that is currently a small fraction of total supply could meet all essential needs for efficient end-use devices, even if that town's grid were completely isolated. In most places, standard improvised power sources [Foget & Van Horn 1969; Black 1971], such as motors driven backwards by car and truck engines, would suffice to continue life pretty much as usual. As in a superinsulated house, the stretched time-constants and the greater scope for improvised supply would make energy efficiency the key to energy resilience.

If this pattern of efficient end-use devices were widespread, baseload power from hydro, cogeneration, etc. could be wheeled for very long distances without straining regional interties, and petroleum-dependent peaking plants would not have to be fired up. Fuel stockpiles for any required thermal plants or cogenerators would be greatly stretched; indeed, cogenerators with flexible boiler designs would often be able to run on locally available wastes. Greater cogeneration in oil refineries and chemical plants (most of which should be net exporters of electricity), besides being economically profitable, increases the plants' self-reliance and ability to serve local users in grid failures.

Additional peak-shaving measures can produce similar benefits in both routine and emergency operation. Peak-shaving cooperatives [Energy & Defense Project 1980:156], expanded power brokerage among utilities (successfully used in Florida), and utility payments to communities for peak-shaving (as by Pacific Gas & Electric) are among the institutional mechanisms proven in the past few years. During the 1977-78 coal strike, DOE curtailment of uranium enrichment shaved about 3 GWe off the regional electric load; since enriched uranium, aluminum, and other electricity-intensive products are easier to store than electricity itself, the existence of such processes in the load mix offers further load flexibility, with the carrying charge on idled plant operations often much lower than the marginal cost of peaking power today.

*If 12 VDC could be used: most household devices currently use 117 VAC, though small inverters for recreational use are cheap and fairly common. Future homes wired for low-voltage DC, e.g. from photovoltaics, would use DC end-use devices, and if these were compatible with standard car electrical voltages, flexibility of emergency supply would be greatly increased.

Among the most important benefits of energy efficiency to the nation and to the individual consumer is the displacement of marginal supplies. That is, efficiency improvements can provide unchanged energy services not only with less total energy, but with less in particular of the energy that comes from the costliest or most vulnerable sources. Thus, decreases in total oil consumption would normally be reflected as decreases in the use of oil from the least attractive source--OPEC and other imports.

This thesis is easily illustrated by arguing that U.S. oil imports can be eliminated by about 1990 by two relatively simple measures, neither of which has been seriously considered in Federal energy policy. The prescription is distressingly simple: stop living in sieves and stop driving Petropigs. The sieves (buildings) are so leaky that just basic weatherization and insulation of American buildings could save over 2.5 million bbl/d of oil and gas by 1990, at an average cost of about \$6-7/bbl, and a similar amount at a similar price during 1990-2000 [Ross & Williams 1979; SERI 1981]*. The Petropigs (gas-guzzling cars and light trucks), however, are a more complex problem.

Gas-guzzlers have such a low trade-in value that they have been trickling down to low-income people who can afford neither to run nor to replace them. These cars are thus remaining in the stock longer when they should be turning over faster. (This is especially damaging because fleet efficiency is a geometric, not an arithmetic, average: a fleet which is 80% 60 mpg and 20% 10 mpg has an average efficiency of 30 mpg, not 50 mpg.) Just as buildings can be fixed up faster if efficiency loans from, say, utilities (Appendix A) relieve people of the up-front capital burden, so gas-guzzlers can be replaced faster if investment that would otherwise go to increase energy supplies were instead loaned or given out for car replacement. For example†:

- Rather than spending \$20 billion (plus perhaps \$68 billion later) to subsidize synfuel plants which will probably never be competitive even with oil at any particular price [Congressional Research Service 1981], the U.S. could save more oil faster by using some of the same money to pay at least half the cost of buying people a diesel Rabbit™ or equivalent--provided they would scrap their Brontomobile to get it off the road. (It cannot just be traded in, because then someone else might drive it; it must be recycled and a death certificate provided for it.)

*Special mechanisms are available for accelerating retrofits [id.]. That used by Canadian utilities to retrofit metropolitan Toronto and Montréal from 25- to 60-Hz electricity--fleets of specially equipped vans modifying all the end-use devices in each neighborhood, one at a time--could also be used, by the public or private sector, to tighten, insulate, and solarize buildings.

†The supporting calculations have been published elsewhere [Lovins 1981b].

- Alternatively, the U.S. could get a 5-year or shorter average payback against synfuels by paying people at least \$200 for every mpg by which a new car improves on a scrapped one. (People who scrap a gas-guzzler and do not replace it should get a corresponding bounty for it.)

- Instead of merely redirecting synfuel subsidies into better buys, as in the two preceding examples, it would be still better to abolish the subsidies and use a free-market solution. The U.S. car industry plans to spend of the order of \$50 billion on retooling during 1985-95 [von Hippel 1981:101]. If in addition the industry spent as implausibly large a sum as \$100 billion extra during the 1980s--probably enough to rebuilt Detroit--on retooling to convert the average car made, in one giant leapfrog, to 60 mpg--20-30 mpg worse than the best prototypes today--and then spread that marginal retooling cost over a new U.S. fleet of cars and light trucks, then the average cost would average \$770 per vehicle, and buyers would recover that cost from their gasoline savings, at \$1.40/gal., in 14 months.

The trouble with this last illustration is that Detroit does not have the money. But the oil industry does, and is currently spending it on extremely expensive and risky drilling. If instead Exxon drilled for oil in Detroit, loaning the car-makers money for retooling to state-of-the-art efficiencies, everyone would be better off (assuming some solution to the obvious antitrust problems), and Exxon would be virtually certain of finding a vast pool of saved oil, producible (not extractable) at over 5 million bbl/d for under \$7/bbl.

These examples are perhaps a trifle whimsical, but they have a serious point. Switching to a 60-mpg fleet of cars would save nearly 4 million bbl/d--two-thirds of the entire 1980 net rate of U.S. oil imports, greater than the imports from the Gulf, two and a half Alaskan North Slopes, or eighty big synfuel plants. Similar action with light trucks would save a further one and a half million bbl/d, or about one North Slope*. These plus weatherization--in short, just the two biggest oil-saving measures--would, if pursued for a decade or so to a level well short of what is technically feasible or economically worthwhile, more than eliminate all U.S. oil imports. They would do this before a power plant or synfuel plant ordered today would deliver any energy whatsoever, and at about a tenth of its cost.†

*A more modest shift to 40 mpg would save almost 3 million bbl/d in cars and 1 million bbl/d in light trucks [von Hippel 1981:95].

†The United Auto Workers and several private analysts have been proposing accelerated scrappage for at least six years. The Federal government has not yet paid attention. The one officially sponsored study [Energy & Environmental Analysis 1980] used such artificially restrictive assumptions that savings were very small and expensive. DOE's supposedly encyclopedic survey of options [1980] does not mention the possibility. DOE's senior oil-backout analysts had not done even back-of-the-envelope arithmetic about it by November 1980. Even Gray & von Hippel [1981] omit it, although they expect a 60-mpg fleet by about 2000 anyhow.

6.4. Economic priorities.

It may be argued that what can be done by 1990 is not a sufficient guide to what should be done right now. By way of further illustration, therefore, let us consider five ways in which the sum of \$100,000 could be spent to reduce dependence on imported oil over the next ten years. These examples are not meant to be sophisticated calculations--they assume, for example, that real oil prices will remain constant, and they do not discount future savings (dollar amounts are all in real 1980 terms)--but their qualitative point is clear.

1. Use the \$100,000 as seed money to catalyze a door-to-door citizen action program of low-cost/no-cost weatherization in particularly leaky buildings. (Such a program does not involve insulation, but only plugging obvious holes. In a typical U.S. house these total more than a square yard, enabling the wind to whistle through the house.) Such seed grants totalling \$95,000 were in fact made by ACTION, HUD, DOE, and community-development block-grant programs to the industrial town of Fitchburg, Massachusetts in 1979. With some imaginative red-tape-cutting by ACTION staff, the grants led to the establishment of ten local training centers, each of which, between October and December, ran 25-30 workshops per week, each lasting about 45-90 minutes. (The Boston energy office is now planning to run abbreviated versions on rush-hour subway platforms.) The Fitchburg program was especially directed at low-income people (under \$14,000/y for a family of four), living mainly in old, 2- and 3-family frame houses. Of the roughly 10,000 households in town, 1728 sent someone to a workshop and received a free retrofit kit. Volunteers helped with installation where needed. About 1300-1400 houses were weatherized in ten weeks--mostly in six or seven weeks after word got around. Each weatherized household saved an average of about \$350 in the first winter. The total oil saving for the town was about \$615,000 in the winter of 1979-80 alone. (Using this program and its umbrella organization--Fundamental Action to Conserve Energy--as a model, similar programs were established the following year in several dozen nearby towns.) From this example we find that investing \$100,000 (rounding up from the actual cost) saves, over the first ten years alone, about 163,000 barrels of heating oil, corresponding to perhaps 180,000 barrels of crude oil, at an average cost of about 61¢/bbl.

2. Use the \$100,000 to convert 44 cars, by replacement, from 15 to 60 mpg (assuming von Hippel's conservatively high marginal cost [SERI 1981] of \$2263/car: the actual cost is almost certainly lower than that). Each car will save (if driven an unchanged 10,000 mi/y) 500 gal/y or 11.9 bbl/y of gasoline*, equivalent to about 13 bbl/y of crude oil. The 44 cars over 10 years will

*Actually somewhat less for replacement at the margin, since the average car sold in the U.S. in 1981 has an on-road efficiency ca. 20 mpg, not 15.

therefore save a cumulative 5830 bbl of crude oil at a cost in the vicinity of \$19/bbl--about the same as for inefficiently executed building retrofits.

3. Invest the \$100,000 by buying 2940 barrels of OPEC oil at \$34/bbl, put them into a hole in the ground, and call it a Strategic Petroleum Reserve. While sitting there the oil will perform no direct energy services, but will presumably cushion against supply interruptions [Deese & Nye 1981; Davis 1981]. The annual cost: of order \$1/bbl for storage and (currently) \$5-6/bbl carrying charges. After 10 years, if the reserve has not been drawn upon, the 2940 barrels of oil will still be there. They represent an investment cost of \$34/bbl which is probably all recoverable, plus a ten-year storage and carrying cost of the order of \$60-70/bbl, which is not*.

4. Spend the \$100,000 on capacity to make synthetic fuels from coal or shale. Using a reasonable--and most likely conservative--whole-system capital investment of \$40,000 per daily barrel, the capacity bought will have the potential, if it works, to produce 2.5 bbl/d (about 9000 bbl/10 y) from about 1990 to 2020. By 1990, however, it will have produced nothing. The plant-gate price of its future output will probably be considerably in excess of \$40/bbl [Congressional Research Service 1981]; the retail price, perhaps \$60-90/bbl.

5. Spend the \$100,000 on a small piece of the proposed Clinch River Breeder Reactor. After ten years it will probably have produced nothing. It may thereafter deliver electricity at a price equivalent to buying the heat content of oil at upwards of \$370/bbl (23¢/kW-h, about the same as from presently commercial but expensive--\$7/Wp--solar cells with a cheap optical concentrator). The CRBR technology stands no chance of competing even with the costliest conventional alternative (light-water reactors) until well past the year 2050 [Lovins & Lovins 1980:70ff; Stockman 1977].

It is perhaps superfluous to note that the official energy policy of the United States has lately been to pursue these options almost exactly in reverse order, worst buys first†--worst buys in terms not only of money but of ability to produce an immediate, continuing saving in oil imports. One is impelled to wonder whether we might not buy more resilience by stockpiling, not oil, but Fiberglas®, weatherstripping, and other materials for weatherizing buildings.

6.5. National least-cost scenarios.

How do these arguments apply to all forms of energy throughout the national economy? Two detailed 1980-81 analyses have addressed this question.

*If world oil prices rose during storage, the oil would appreciate; but the same is equally true of each barrel saved by our previous two options. In those cases, one can consider either that imported oil has been avoided or that domestic oil has been left in the ground as a "strategic reserve" with no purchase or storage costs.

†The new Administration, however, appears--wisely--to have reduced its synfuel goal from Congress's 2 Mb/d in 1992 to 0.5 Mb/d in 1990 [DOE 1981a:23].

One, by Roger Sant and his colleagues at the Mellon Institute's Energy Productivity Center, an industry-supported "think tank" in Arlington, Virginia*, is an expansion of Sant's pioneering analysis [1979] of "The Least-Cost Energy Strategy," which "minimizes consumer cost through competition." That 1979 analysis showed that if, for about a decade before 1978, Americans had simply bought at each opportunity the cheapest means of providing the energy services which they actually received in 1978, then in that year they would have bought about 28% less oil, 34% less coal, and 43% less electricity than they did buy, and would have paid about 17% less for their energy services than they did pay. Efficiency improvements would have made up virtually all the difference.

In 1980-81, the same analysts then used an even more detailed model, in which many hundreds of supply and efficiency options can compete freely, to examine the result of economically efficient investments during 1980-2000. They found [Sant et al. 1981] that even if real GNP grew by 77%, primary energy use would rise by only 11%, and all the growth would be in the industrial sector as others became efficient faster than their activity levels grew. Electricity demand would probably be stagnant for at least the first decade. Efficiency improvements (and some renewable sources) would so dominate the cost-effective choices that investment in conventional supply would virtually cease, and it would hardly be worth finishing building most of the power plants now under construction. The fraction of GNP used to buy energy services would go down, not up, so that far from driving inflation, the energy sector would become a net exporter of capital to the rest of the economy. Imported oil--the costliest option except for new synfuel and power plants--would rapidly dwindle to about zero, simply because it has already priced itself out of the market. It cannot compete with efficiency improvements (or with most renewables) and will therefore essentially eliminate itself without special policy attention.

These conclusions have been strongly confirmed by a parallel but independent analysis carried out by dozens of consultants coordinated by the Solar Energy Research Institute [SERI 1981] at the request of then Deputy Secretary of Energy John Sawhill. The SERI draft report assumes an 80% increase in the 1977 real GNP by 2000, and major increases in personal income, comfort, and mobility. It also tests efficiency and renewable investments against alternative supply costs which, while not as low as Sant's, are still well short of realistic marginal costs. It embodies many technical conservatisms, and assumes no technology which is not already in operation in the United States. Yet it shows how primary energy use could decrease to 13-18% below the 1980 level, and how, with economically worthwhile investment in presently available renewable sources as well, the use of nonrenewable fuels would drop by nearly half.

*On 1 October 1981, this institution was succeeded by Applied Energy Services, Inc., which is carrying on similar work for profit at the same address.

At that level, not only could oil imports and most frontier oil and gas become unnecessary, but a good deal of conventional lower-48 oil and gas could also be shut in as a dispersed "strategic reserve" with no extra storage costs.

Total demand for electricity, too, would probably decline. With cost-effective efficiency improvements and onsite solar heating systems, the electrical growth rate during 1978-2000 would be about 0.2%/y. With cost-effective wind, industrial cogeneration, and onsite photovoltaic investments added, the "growth" rate would become zero to minus 1.4%/y. Under the former assumption (no wind, cogeneration, or photovoltaics), national electric supply would be ample even if no new plants were commissioned after 1985 and if all oil-fired, gas-fired, and old power plants had been retired by 2000. Under the latter assumption (all cost-effective renewable and cogeneration investments), supply would exceed demand by about a third--more than a sufficient margin to phase out all nuclear plants as well if desired and still have capacity to spare.

Thus the U.S. could enter the twenty-first century with a greatly expanded economy, zero use of oil, gas, and uranium in power plants, total consumption of fossil fuels reduced from about 70 q/y in 1980 to about 40-50 q/y in 2000, zero oil and gas imports, and ample domestic oil and gas in conventional, accessible sites to last for some further decades of transition to sustainable sources--and could accomplish all this simply by using energy in a way that saves money. Nor is this a peculiarly American result. Similar studies, some in even greater detail, have shown comparable or larger savings for a wide range of other industrial countries, many of which are already more energy-efficient than the U.S. These analyses, which we have reviewed elsewhere [Lovins et al. 1981], show that probably all countries can cost-effectively improve their energy efficiency by severalfold--a fact of considerable importance for the long-term balance of world oil supply and demand. It is especially encouraging that this could be achieved simply by permitting market forces to achieve the optimal economic balance between investments in efficiency and in new supply. A vulnerability-minimizing, oil-saving strategy is also a least-cost strategy. It is not inimical to national strength, security, and prosperity, but is the very means of obtaining them.

We have not considered here the many other advantages of such a policy: in reducing price volatility and price increases, in countering inflation and unemployment, in reducing environmental and social impacts, in moderating tensions and inequities, and in alleviating the global risks of climatic change [id.] and nuclear proliferation [Lovins & Lovins 1980]. All these effects are important. But they, and energy vulnerability itself, need not be considered at all in order to conclude that greatly improved energy efficiency should be a

dominant national priority on economic grounds alone. Since this study is concerned with energy vulnerability and resilience, not with energy policy generally, we shall not consider here, as we have done elsewhere [id.:91-125], the policy instruments by which such a result can best be achieved. Although our own preference is for a combination of truthful prices (with subsidies and other distortions removed) and of purging the market imperfections which inhibit efficient response to price signals, a more detailed consideration of how best to achieve the ends we have described is more in the realm of political philosophy than of our assigned subject. We therefore turn instead to the other half of an inherently resilient energy system: the widespread use of renewable energy sources matched in scale and quality to their task, the so-called "soft technologies" [Lovins 1977b,1978]*. But while considering these sources, we must not succumb to the "gadget-on-the-roof" syndrome and lose sight of the cornerstone of any resilient energy system: highly efficient energy end-use. The benefits of that efficiency are as broad and indispensable as Lao-tse summarized them two and a half millenia ago in Tao Te Ching 59:

In managing affairs there is no better advice than to be sparing.
 To be sparing is to forestall.
 To forestall is to be prepared and strengthened.
 To be prepared and strengthened is to be ever successful.
 To be ever successful is to have infinite capacity.

*Sweden's energy R&D budget has reflected both priorities since 1978. The 1981-84 proposal [Energy R&D Commission 1980] comprises 36% efficiency (over half of it in buildings), 40% renewables, 3% district heating, and 7% miscellaneous (system studies, basic research, and overheads). The balance, 14%, is for nonrenewables--chiefly prior commitments in fusion and in fission safety and waste management, since over 3/4 of Swedes voted, and Parliament enacted, that Sweden will phase out nuclear power by 2010.

7. INHERENTLY RESILIENT ENERGY SUPPLIES

Our analysis of efficiency improvements in the preceding Chapter concluded that they are being implemented at an astonishing rate (Chapter 5.3) because they are the cheapest way to provide energy services. This trend should be encouraged in national policy, not only to save money, but because more efficient energy use greatly increases individual and national security. This Chapter will first build on that conclusion by arguing that when used in conjunction with greatly increased energy efficiency, there is a particular form of energy supply--appropriate renewable energy sources--that offers similar security benefits. We shall then compare these sources in other respects with the technologies which dominate present Federal energy policy. To give at least a glimpse of the complexities and pitfalls of economic comparisons* between renewable and non-renewable energy systems, we shall survey some generic features of those systems' internal and external costs, and call attention to issues that arise when renewable sources are integrated into existing, mainly non-renewable, energy systems. With that foundation, we shall then briefly assess the technical and economic status of renewables, with special attention to some rapidly emerging technologies which hold special promise for increasing energy preparedness.

7.1. The resilience of appropriate renewable sources.

In Chapter 6 we compared two types of houses: a normal, thermally inefficient house which rapidly reaches uncomfortable, even intolerable, temperatures unless continuously supplied with space-conditioning energy at large average and peak rates; and a superinsulated house which maintains tolerable temperatures with no outside energy whatever, and comfortable temperatures with virtually any small source--especially a simple renewable source. We showed that the latter type of house is cheaper, makes its occupants virtually invulnerable to interruptions in their supply of space-conditioning energy, and enables them to meet their space-conditioning (and other) household energy needs with much smaller, simpler, and cheaper renewable sources than they could have done in

*More fundamentally, any attempt at rigorous calculation and comparison of the costs, risks, and benefits of any energy technology is bound to run up against a host of serious theoretical and practical obstacles, which are beyond the scope of this study but have been surveyed elsewhere [Lovins 1977; Junger 1976; Council for Science & Society 1979].

the inefficient house. Thus we demonstrated a synergism between efficiency and renewables, and a correlation between favorable economics and resilience.

The entire national energy system today is like the inefficient house--dependent for survival on continuous supplies of costly and vulnerable energy. It can and should be made like the superinsulated house--cheaper, less dependent, more resilient. If this is not done, no kind of energy supply can long sustain the American economy, and the marginal supplies required even in the short term are so precarious as to pose a grave threat to national security.

Federal energy policy has long assumed, as was widely believed a decade ago, that efficiency gains can only be small (perhaps 10-20%). If this were true, the U.S. would need far more energy in the future, and would have to get much of it by expanding the same kinds of inherently vulnerable energy systems which are of such security concern today. There would be no alternative to "Strength Through Exhaustion" (of domestic resources). A future of "The Past Writ Large" would mean ever greater vulnerability, with no respite in sight.

Analysts who hold this view do not readily appreciate the profound structural changes which cost-effective levels of energy efficiency can bring. The SERI analysis [1981], for example, showed how the U.S. can achieve strong economic growth over the next twenty years with--indeed, by--investing far more heavily in energy productivity, so as to achieve a proper balance with energy supply investments. If this were done, as we showed in Chapter 6, the most vulnerable sources (imported oil, LNG, frontier oil and gas, nuclear power) could be phased out entirely, and dependence on other vulnerable systems (central power stations and their grids, oil and gas pipelines, Western coal) could be greatly reduced. But a result of even greater importance is that far more resilient renewable sources could cost-effectively supply up to 35% of total national energy needs in 2000--and approximately 100% within a few decades thereafter [Sørensen 1980; Lovins et al. 1981]. Sustainable sources, not exhaustion, would then underpin long-term prosperity and security.

Thus greater energy efficiency has the security advantage that it will rapidly eliminate the most costly and vulnerable energy systems. The remaining demand will then be so small (a quarter less in 2000 than today, and declining thereafter) that insecure and dwindling fuels can be most cheaply and easily replaced by almost invulnerable renewable sources--sources which, as we shall show below, are the cheapest long-run sources available after efficiency gains. Far from being minor, unimportant sources, the many kinds of appropriate renewable technologies would make a major and soon a dominant energy contribution. Thus a major structural change in energy supply would become both possible and economically preferable--completing the transformation of the American energy

system from living on energy capital to living on energy income, and from vulnerability to resilience.

By "appropriate" renewable sources--"soft technologies" for short--we mean those which supply energy at the scale and in the quality which will provide each desired energy service at least cost to the consumer. Chapter 5 showed how a mismatch of scale between source and use can roughly double energy service costs by incurring the costs and losses of a vast distribution network. Proper scale for each task can minimize those costs and losses. Likewise, Appendix A describes how supplying energy of the right form for each task can minimize the costs and losses of energy conversion. Thus the 92% of U.S. delivered energy which is needed in the form of heat, or as a portable fuel for vehicles, is most economically supplied in those forms--not as electricity, which is cost-effective only for a premium 8% of all delivered energy needs. This is because electricity is conventionally generated in costly, complex machines which lose two-thirds of the energy in the fuel in order to make a high-quality energy form. If that quality is not used to advantage--if, for example, the electricity is used for space-conditioning--then the whole conversion process was a waste of money and fuel. Most "appropriate" sources are thus non-electrical.

Renewable sources are often described as "new," "unconventional," or "exotic." None of these labels is accurate. To be sure, many renewable energy technologies have been greatly improved by modern materials and design science. But this is only the latest stage in an evolutionary process stretching back for hundreds, even thousands, of years [Butti & Perlin 1980]. Such technologies as passive solar design, windpower, and biomass alcohols were well-known in rather sophisticated forms millenia ago. Solar concentrators were used in the Battle of Syracuse (the only significant known military use of solar technology). Flat-plate collectors are two centuries old; photovoltaics and solar heat engines, over a century. Repeatedly, many solar technologies have become respectably mature only to be cut off by the discovery of apparently cheap deposits of fuels, whether wood in the Roman Empire, coal in industrializing Britain, or oil in our own time. Each time, as scarcity and a sense of insecurity returned, the renewable sources have been reinvented. The latest re-emergence may be the last time it is necessary to repeat this process.

The most obvious feature of renewable energy sources is that they harness, not a deposit of fossil or nuclear fuel that is very unevenly distributed in the earth's crust, but a variety of direct and indirect fluxes of solar energy*

*We do not consider here geothermal energy or tidal power (moonpower), since neither is renewable in principle. In the right sites and with due attention to their considerable potential for environmental damage, however, both can be locally important for providing heat and electricity respectively.

which are distributed freely, equitably, and daily over the entire surface of the earth, and are not subject to embargoes, strikes, or other major interference. "Equitably" does not mean equally. The flux of solar energy fluctuates in time and space, both according to the predictable pattern of the earth's rotation and orbit and according to the variations of weather, which tend to be more stochastic (random in detail but statistically predictable in general pattern). These variations, however, are quite well understood [Sørensen 1979], and a properly designed renewable energy system can readily cope with them--given efficient energy use--by using the combination of sources and design parameters suitable to each site and application. Sources can be chosen which tend to work best in different weather patterns, i.e. which have negatively correlated output: cloudy weather, bad for solar cells, is often good for windpower, and droughts, bad for hydro, are good for solar cells. Existing storage, like water behind hydro dams, or on-site storage can be provided. End-use devices can be designed with long time constants to cope with intermittence. Solar energy can be harvested and converted from vegetation at one's convenience rather than captured instantaneously as direct solar radiation. Sources can be integrated over a sufficient area to average out fluctuations in the renewable energy flux or in end-use patterns.

The intermittence of renewable energy fluxes is smaller than one might imagine. A typical wind machine in Denmark needs only ten hours' storage to be as reliable as a typical light-water reactor [id.:582f]. The statistical complementarity of wind, hydro, and solar cells (photovoltaics), especially if dispersed over a sizeable area [Kahn 1979:319f], can make a grid combining them more reliable than one using fossil- or nuclear-fueled steam plants. Such results often surprise designers of today's "hard technologies." But they need to appreciate better the unreliability of their own systems. In principle the need to design for fluctuation is nothing new. Today's energy systems fluctuate too, far less predictably, whenever there is an oil embargo, coal strike, etc., and this kind of fluctuation must also be guarded against by design. Failure to do this adequately--to consider the impact of surprises, failures, and deliberate disruptions--has indeed helped to make today's energy system as vulnerable as it is. Fluctuations in renewable energy fluxes are in this sense better understood and more predictable than those in the supply of conventional fuels and power*. The calculations that go into writing a weather forecast

*They also tend to be less severe. Kahn [1978:33], for example, notes that in a Pacific Coast wind array, "a lull...which reduced power to about 1/3 the summer mean would last for 15 hours with 95% probability. For 99% availability of [at least]...1/6 the summer mean, the lull would last about 10 hours. For comparison, however, major outages of LWR generators have an average duration of 300 hours [at zero output]."

or an ephemeris of the motions of the sun are considerably more reliable than those that predict reactor accidents or Saudi politics. One can have greater confidence that the sun will rise tomorrow than that someone will not blow up a supertanker in the Straits of Hormuz. It can be cloudy for days or weeks (not, as noted below, a serious impediment to solar systems designed for cloud), but the sun cannot be totally eclipsed for months like an oil-import cutoff.

We have been careful to state that appropriate renewable sources--not all renewable sources--offer economic and security advantages. Unfortunately, the overwhelming emphasis in Federal renewable programs so far has been on the least economic and least resilient renewables, especially the central-electric ones. The historic reasons for this tendency to "make solar after the nuclear model," as two veteran observers remarked [Hammond & Metz 1977], are rooted not in economic rationality but in mere force of habit. The R&D managers assumed the desired product was baseload electricity, even though the 8% of delivered energy needs that can give us our money's worth from electricity--a special and very expensive form of energy--are already met twice over by power stations already in operation. Federal energy agencies and their major contractors also assumed, all but universally, that the way to develop renewable sources was to build prototypes--first of megawatt scale, then working up in stages to gigawatt scale--just as if the product were a new kind of *fission reactor*. They apparently assumed that anything else, or anything designed for a market other than utilities, "would fall short of a major contribution" [*id.*]. Believing solar contributions would be small and far in the future, they sought to carry out their self-fulfilling prophecy by emphasizing the least economic designs.

Thus considerable engineering talent, and contracts probably amounting to tens of millions of dollars, have been devoted to conceptual designs for solar power satellites, even though the cheap, efficient solar cells which they presuppose would deliver far cheaper electricity [Foreman 1981] if put on roofs in Seattle. In that form they would be virtually invulnerable, whereas in orbit they could (as Hermann Oberth pointed out a half-century ago) be turned into Swiss cheese by anyone who cared to buy a weather rocket and launch a load of birdshot into the same orbit in the opposite direction, there to meet the vast collector areas of the satellite every half-hour at 36,000 miles per hour.

Likewise, DOE has spent most of its wind budget on developing multi-MWe machines with blades like a 747 wing. They are enormous, complex, prone to high-technology failures, and useful only to large utilities. Each unit costs millions of dollars and is made, rather like a jetliner, by a highly specialized aerospace firm, then shipped across the country to the site. In contrast, some U.S. manufacturers have independently developed wind machines in the kWe or tens-of-kWe range which have simple bolt-on sheet-metal blades, no brushes,

one bearing, two or three moving parts, and essentially no maintenance requirements (p. 176). Any handy person can make and use them. They are available now (p. 246) at lower costs per kWe than DOE estimates its designs will drop down to.

An anecdote reveals the philosophical divergence. After spending tens of thousands of dollars on computerized electronic sensors to shut down a DOE wind machine if it started to vibrate too much, its designers visited the 200-kWe Gedser machine operated decades ago in Denmark. Its vibration sensor was a saucer containing a large steel ball. If the tower shook too much, the ball would slop out of the saucer and fall down, and a string attached to it would pull a switch. (There is a postscript: the DOE sensors proved unreliable, and had to be supplemented by a closed-circuit TV camera monitoring a painted film can hung from a string so the operators could see when the tower shook.)

There is thus a considerable difference between the renewable sources on which most Federal attention has been focused and those sources which merit it by their economic and security benefits. This difference is partly in unit scale and simplicity. It is partly in the types of technologies considered: we have not, for example, found an instance where central-receiver solar-thermal-electric systems, or ocean-thermal-electric conversion (OTEC), or solar power satellites, or monocultural biomass energy plantations, look economic or necessary. And the difference is also partly institutional and psychological. DOE has tended to favor "inaccessible" technologies which reinforce the supposition that ordinary people should be mere passive clients of remote technocracies. This in turn encourages people to think that if energy supplies are disrupted, "the Government" will take care of it. We believe it is important, if energy preparedness is to become a reality, that people feel empowered to use their own skills, solve their own problems, and largely look after themselves. This requires in turn that they have, and know that they have, most of the technological means to do so.

We premise this Chapter, then, on the assumption of intelligent design based on sound economic principles, not on mere habit. Given such good design, renewable energy systems can systematically fulfil their outward promise of being difficult to disrupt. Consider, for example, how soft technologies can avoid most or all of the twelve sources of vulnerability identified in Chapter 2.1. They are unlikely to bring the user into contact with dangerous materials (explosive or radioactive); even renewable liquid fuels (alcohols and pyrolysates) tend to be much less hazardous, in flammability and toxicity, than their petroleum-based counterparts. (A possible exception is that certain types of solar cells can be made with small amounts of cadmium, arsenic, or other highly toxic materials, and the burning of a cell-bearing house could release these to the

environment in quantities of tens or hundreds of grams. Highly efficient cells can also be made, however, at similar or lower cost from other materials which are either nontoxic or refractory.) Far from having limited public acceptance, appropriate renewable sources enjoy a 90+% complete consensus unmatched by any other category of energy technologies [Farhar et al. 1980; Milstein 1978]. With the exception of existing large hydroelectric dams appropriate for the few concentrated end-uses of electricity, such as smelters, sensibly designed renewable sources avoid centralization of supplies. Because they collect renewable energy flows where they are, rather than mining a fuel elsewhere and transporting it, they do not suffer from long haul distances. Their usual range is from inches or feet (in buildings) to miles or perhaps tens of miles in some bioconversion systems. Limited substitutability is seldom characteristic of renewable sources: many bioconversion systems, for example, can cope with an immense range of feedstocks within broad limits of wetness and carbon/nitrogen ratio, and some, like the thermochemical processes (p.244), can make the same widely usable liquid or gaseous fuels from any cellulosic or woody feedstock regardless of origin. Likewise, efficient solar collectors can be made out of a vast range of materials--glass or plastic or recycled storm-doors for glazing, steel or aluminum or wood or paper or plastic film (or even beer cans) for absorbers, rocks or masonry or water-filled oil drums or recycled bottles for heat storage, or even a hole in the ground and some brine--a solar pond--in lieu of all these components (p.241). The range is limited mainly by one's imagination.

Unlike large turbogenerators, renewable sources of electricity are difficult to damage if synchronization breaks down. A solid-state grid-interface device can enable them to cope with unusual or rapidly changing electrical conditions which normal electromechanical devices could not handle (p.226). Renewable sources integrated into a grid require synchronization, but with proper design they can also, unlike other sources, work as well into a local load without synchronization, in isolation from the grid, or even on direct current. The tendency of properly designed renewable sources to distribute energy in the final forms in which it will be used, such as heat or unspecialized vehicular fuels, eliminates many of the inflexible delivery systems that make their nonrenewable counterparts so logistically complex. The cheapest and most effective renewable designs also tend to avoid interactions between energy systems--whether by substituting convective circulation for active pumping in a thermal system or by using wind stirring or solar process heat in bioconversion. Although many soft technologies have modestly high capital intensity, theirs is considerably lower (as we shall show below) than their competitors', and they have an even greater advantage in avoiding long lead times and

specialized labor and control requirements. Their distribution systems, too, are seldom large enough to make distribution of noxious materials a significant concern. While all these agreeable properties are not a necessary part of a renewable energy system, they will generally result from design for least cost.

Properly arranged soft technologies also satisfy most or all of the principles of resilient design (Chapter 4.4). They are mainly dispersed to match their uses (Chapter 5.1). Their large numbers, diversity, and overlapping end-use functions can offer both numerical and functional redundancy--as in a town whose blend of a large number of different sources of electricity (wind, microhydro, solar cells, solar ponds with heat engines, etc.) or of biomass liquid fuels offers built-in backup in case particular devices or types of devices have trouble. Electricity-generating soft technologies can readily be interconnected while maintaining node autonomy--the ability to stand alone at need (Chapter 7.2.3). They provide far greater functional flexibility in adapting to changes in operating conditions and feedstocks than virtually any "hard technology" could tolerate. Their design can readily incorporate--and often will for economic reasons--modularity and standardization, as in mass production of solar cells or site-assembly of mass-produced collector components, although the diversity of people and institutions pursuing them will help to prevent a degree of standardization that might serve to propagate design errors. That safeguard is reinforced by a speed of evolution that has compressed generations of technical development into a few years. Being made of relatively cheap and simple materials and using relatively undemanding processes, soft technologies can readily incorporate internal decoupling and buffering without unreasonable extra cost. Their simplicity and forgiveness, their accessibility to and reproducibility by a wide range of actors, and their social compatibility are among their main hallmarks. There is hardly a quality conducive to resilience which they do not have in abundance; hardly one conducive to brittleness and vulnerability which, with proper design, they cannot avoid.

These resilient characteristics, however, are not a sufficient basis for choice. Indeed, our discussion of efficiency improvements in Chapter 6 ignored their security benefits and considered only their economics. To be equally conservative, we should take a similar course here. We therefore consider next some generic problems of comparing energy technologies, as a prelude to surveying the state of the art in appropriate renewable sources.

7.2. Assessing soft technologies: generic issues.

Calculating the economics of renewable compared to nonrenewable energy sources (or renewables vs. each other or vs. efficiency improvements) is easy

to describe but very difficult to do properly. In principle, the economic value of renewables depends both on the price of the energy they deliver and on the price of the energy they replace. Both are highly uncertain. Both can be evaluated only with reference to a particular energy service delivered to a final user. Market price reflects some "internal" costs but excludes others ("externalities"), such as unregulated forms of pollution, vulnerability, or other costs paid by neighbors or by society as a whole, not specifically by the buyer. We therefore consider internal and external costs separately.

7.2.1. Internal costs.

Renewable energy systems have no fuel cost (except for the feedstock to bioconversion systems and, perhaps, water rights for some hydro). If well designed and built, they also tend to have low operating and maintenance costs. (If not, long-term economic performance can be quite sensitive to those costs.) The price of renewable energy therefore depends mainly on:

1. Their initial capital cost. This depends strongly on
 - a. The simplicity, cleverness, and durability of design. These can vary enormously and may bear no relation to the designer's formal credentials: indeed, highly qualified designers may produce the most gratuitously complex designs.
 - b. The marketing structure. A "packaged" flat-plate solar collector system with three or four markups can cost several times as much as an otherwise identical "site-assembled" system with one markup [Worcester Poly. 1978; Godolphin 1981].
 - c. How efficiently the delivered energy is used. This affects, as we noted in the Saskatchewan Conservation House example, the size of the renewable system (which can be altered by tenfold), its performance, and its complexity (as in the replacement of a heat-distribution system by natural convection). Such synergisms can be examined only on a micro design level.

These effects can together change unit prices by factors ranging from ten to perhaps a thousand.

2. The cost of financing them over their lifetimes. This depends on
 - a. Real interest rates, which depend on perceived risk and should therefore be lower for many renewables [Kahn et al. 1980].
 - b. Working capital requirements. These are related to capital intensity by construction time, payback time, and shape of cash-flow, and again should be more favorable for soft technologies [id.].

- c. Projected operating lifetime, which may be difficult to estimate.
(Some wind machines and flat-plate solar collectors have worked well for decades with little or no maintenance. Badly built, they could have failed in a few months or years. Some designs are much more forgiving of mistakes and environmental insults than others.)
- 3. The amount of energy supplied annually. This depends on
 - a. Quality of design, construction, operation, and maintenance.
 - b. Patterns of energy use. A mismatch between supply and demand patterns could leave some demand unmet or lead to the "dumping" of surplus supply (such as unneeded space heat in the summer).
 - c. Variations in weather and climate.
 - d. Appropriateness of design to local conditions and use patterns.
Some large corporations have been unable to compete in the solar-collector market with some small businesses, not only because the latter had better innovation and lower overheads, but also because they could achieve better performance by matching designs to local weather, building styles, etc.--rather than making a "cookie-cutter" product which is designed for a hypothetical average case and is therefore suboptimized for any actual particular case.
- 4. The amount and type of storage required, if any. This depends on the three factors just listed and on the nature and degree of integration with other renewable or nonrenewable sources. (We shall consider these integration issues further below.)

This may seem, and it is, more complex than one might have expected. But to make matters worse, the price of competing nonrenewable energy is equally imponderable. It depends mainly on

- 1. General and sector-specific inflation in the cost of goods, services, and money, both during construction and afterwards for the project's operating lifetime.
- 2. The relationship between historic and marginal capital costs. (The latter have generally exceeded the former since about 1970.)
- 3. The difficulty of obtaining fuels from ever more remote and awkward places.
- 4. The economic and political policies of fuel-exporting countries interacting with a complex world market and with unforeseeable political exigencies.
- 5. National and local policies regarding trade, legal structures, inflation control, employment, environment, and a host of other factors.

6. Technical reliability and resilience desired.
7. Tax and accounting conventions, tariff structures, and subsidies.
Subsidies to the U.S. energy system total over \$252 billion (1978 \$) historically [Cone et al. 1980], with the nuclear term sufficing to cut the apparent cost about in half [Bowring 1980; Omang 1981]. Tax and price subsidies are currently continuing at a rate of the order of \$100 billion per year [Lovins 1981a]--enough to reduce average energy price by over a third and nuclear electricity price by over half again [Chapman 1979].
8. Salvage values. (For nuclear facilities and wastes these are negative but of unknown size.)

Renewable/nonrenewable comparisons are further complicated by the following problems:

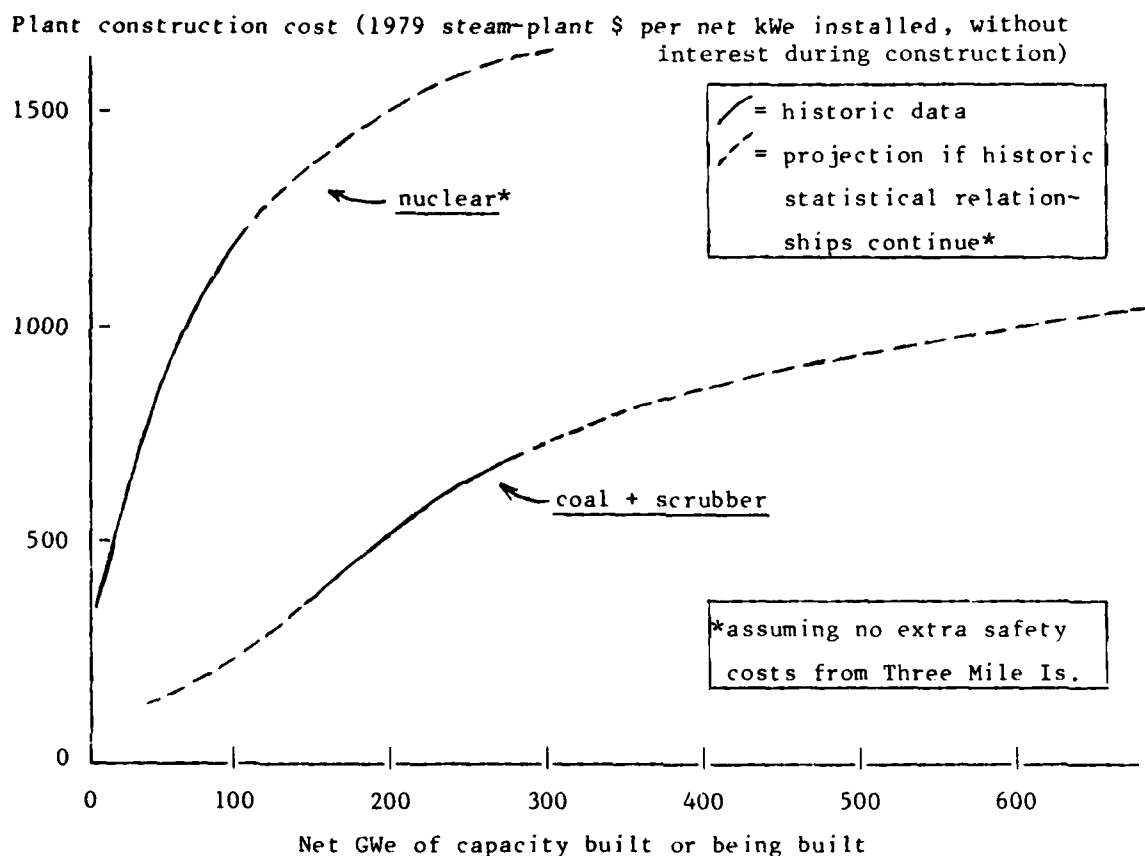
1. Great variation in price quotations even for one product in one market. Identical gas-fired water heaters in identical Southern California apartments differ by a factor of two in retail price and by nearly a factor of three in installed price. Price scatter is larger in solar markets, which are less mature and have more diverse product lines and marketing structures.
2. Extremely rapid technical change, especially for renewables, much of it outside official programs and traditional information channels.
3. Uncertainty about how far, or how, to internalize important externalities (many of which are considered further below).
4. What depletion value to put on nonrenewable fuels and other resources. Their cost was traditionally assumed to be only the cost of mining them, as if that mining did not make their future replacement more costly to society.
5. Asymmetries in tax and price subsidies, generally favoring nonrenewables. Reliable subsidy assessments are very scarce.
6. The many imponderable (e.g. psychological and political) factors that help to determine how far and how fast different available technologies can be put into use.
7. Economies and diseconomies of scale (Chapter 5).
8. The inability of most simulation models used by energy policy analysts to cope properly with diverse, relatively dispersed renewable sources or with their nontraditional processes of market penetration (Chapter 5.3).
9. The need to match any renewable source to its climate, site, applications, and users, in order to achieve best performance at least cost.

10. The difficulty of comparing the storage and backup requirements of complete energy systems containing renewable or nonrenewable components, to achieve a given level of reliability to final users, when there is not a fully satisfactory reliability theory for either type of system, let alone for both in combination.
11. The potential for total-energy systems which provide electricity and heat (and perhaps liquid fuels) and for other types of hybrids (discussed below).
12. The opportunities offered by many renewable sources (but only rarely by nonrenewables) for sharing functions and costs through integration into shelter, food, water, or other systems.
13. The difficulty of identifying such integration opportunities, or indeed many renewable energy opportunities by themselves, without a highly localized and disaggregated analysis.
14. The sensitivity of economic comparisons to minor changes in accounting for inflation, "levelizing" varying costs over the life of a project, discounting the future, etc. Small, seemingly innocuous changes in real discount rate are a commonly used method of reversing the merits of renewable/nonrenewable comparisons.

In view of these complications, it is not surprising that virtually no renewable/nonrenewable cost comparison will prove satisfactory to everyone. Experts often disagree about basic data by factors of severalfold, depending on their familiarity with recent developments and willingness to accept empirical data as "existence proofs." They differ in their assessment of the state of the art or the applicability of certain methodologies. They do not accept other experts' views on how far particular case-studies are more widely applicable. Thus a large number of energy experts, laid end to end, will probably never reach a conclusion about the economics of renewable sources.

The only recourse is to make assumptions and data sources explicit enough so that cost calculations are transparent, scrutable, and easily compared. It must also not be expected that the unit cost of any technology can be represented by a single number. Economic theory indeed requires that each technology (or aggregate of different technologies) be subject to a "supply curve" in which unit price rises with increasing supply. That this is the case for conventional utility power-plants, owing to a complex series of political-regulatory relationships reflecting a public desire to hold constant the perceived social cost of expanding coal and nuclear sectors, is nicely illustrated in the following graph. It plots as supply curves the data obtained by Komanoff's [1981] statistical analysis of historic costs, which explains 92% of the ob-

served variation in the real cost per installed kWe of nuclear plants and 68% for coal-fired plants, with samples of 46 and 116 plants respectively.



Although the shape of the supply curve would probably differ--especially in being concave rather than convex upwards--renewable sources too have supply-curve costs rather than point costs. For example, solar heat collectors small enough to go on a building usually cost less than those which require extra land (usually an artifact of inefficient energy use). Biomass fuel systems which convert special crops--likewise a symptom of inefficient use--incur extra farming and collection costs compared with those that use wastes already harvested, especially where those wastes are currently a nuisance and any new way of disposing of them earns an economic credit. Most official analyses of renewable sources evaluate their costs on the high, steeply sloping portions of their supply curves to which inefficient energy use drives them. The low, shallowly sloping portions, however, reflect a more nearly optimal economic balance between investments in energy supply and in energy productivity, and therefore represent the supply corresponding to the "market clearing price" at which the supply and demand curves cross in equilibrium. Hence energy supply costs cannot be analyzed independently of competition with energy productivity.

Despite all the generic uncertainties of renewable/nonrenewable cost comparisons, four broad principles can often simplify economic choices:

1. Investment decisions should be based not on projected small differences of marginal cost (which are often well within the uncertainty of the data) but rather on how sensitive those costs will be to changes in key variables such as oil price. Basing decisions on sensitivities enables one to "play safe" in an uncertain world. In general, the variations of most policy interest, such as high world oil prices or high inflation, tend to improve the competitive position of renewables still further. Yet soft technologies do not (as Chapter 7.3.1 shows) require such assumptions for their attractiveness, since they can generally compete with present oil prices with considerable room to spare.
2. Differences of internal cost may be less important to many nations than differences not captured in that cost--implications for resilience and self-reliance, employment, equity, balance of trade, etc.
3. In general, the real costs of fossil and nuclear energy are likely to rise and those of most renewable sources to fall. The relative speeds of change in both cases are the subject of great uncertainty and dispute, although the directions of change are empirically undeniable and the fundamental reasons for those changes are all but certain to persist.
4. In general, renewable sources offer far greater scope than nonrenewables for simple, low-technology adaptations suitable for local construction with limited skills and common materials. Such simplified versions cost far less than those normally analyzed; they are more analogous to the improvisations commonly made by individuals at a grassroots level. It is difficult to capture the enormous range of costs reported for such self-help projects, especially those done by low-income people who do not cost their own labor or who do cooperative projects. But in general the real costs to the users are far less--even orders of magnitude less--than for conventional, industrially supplied hardware, and the performance is often broadly comparable and sometimes better.

This last point deserves special emphasis. It is difficult to model, but familiar to anyone who visits community-based energy projects or who reads the many journals (New Shelter, Popular Science, Popular Mechanics, etc.) devoted to self-help and "vernacular technology." What a high technologist would be likely to do with a steel tower, an aluminum extrusion, a Fiberglas® sheet, or

a piece of digital recording electronics can also be done passably well with scrap lumber or lashed saplings, a piece of an old oil drum, a sheet of cloth, or a person with pencil and paper. High technology is not inconsistent with cheapness or simplicity: a recently developed digital recording anemometer for analyzing proposed windpower sites is made of a \$4.95 calculator, cups from two pantyhose containers, and similar odds and ends, then calibrated by driving at known speed down a highway on a calm day while someone holds the gadget out the window. It costs in all around \$10, but performs about as well as commercial versions costing many hundreds or thousands of dollars. There are tens of millions of Americans who would have no trouble making one. Similarly, the project managers for some fancy Federal solar projects were amused, on visiting one experimenter, to find that in testing solar panels he measured their water flow, not with their fancy digital flowmeters, but with a bucket and stopwatch. They were less amused to discover that the National Bureau of Standards calibrates their flowmeters with a bucket and stopwatch.

We do not mean to dwell unduly on "haywire rigs"--the kinds of technology that can be put together from things that are lying around in virtually any farmyard or town dump in the world. But neither can their potential be ignored in favor of the highly refined designs more familiar to well-funded high technologists. Whatever they may think of these odd-looking improvisations, they must at least admit that oil refineries, reactors, solar power satellites, or multi-megawatt wind machines do not offer the same potential for simplified versions at greatly reduced cost. That potential is advantageous enough in normal times; in emergencies it becomes absolutely vital.

Subject to these caveats and uncertainties--the last, the immense range of technical complexity and costs over which many renewable options can be built, being perhaps the most difficult to analyze--illuminating comparisons of renewable/nonrenewable economics are in fact possible, and can compensate for fuzzy data with multiple conservatisms. With good design and careful shopping for best buys, and basing responsible analysis on empirical data (below), many renewable energy systems already arguably offer a pronounced economic advantage (especially at their incremental cost). This advantage is generally increased by doing the still cheaper efficiency improvements first. This economic ranking of marginal sources--efficiency improvements cheapest, then appropriate renewables, then nonrenewables (synfuels and power plants) [Stobaugh & Yergin 1979]--does not take account of external costs and benefits not currently reflected in market prices. Before offering some illustrative numbers supporting our generic conclusions, we must therefore detour briefly into what these externalities are and why they are arguably at least as important as internal costs.

7.2.2. External costs and benefits.

Economically efficient allocation of social resources requires that energy technologies be left to compete freely with each other and to stand or fall on their economic merits. But market prices do not reflect, and are not meant to reflect, many important social costs and benefits. Even if they did, an economically efficient result might not be equitable, and cannot be expected always to coincide with the results of the political process, which is designed to reflect and protect a broad range of interests not represented in market processes. A democracy works by "one person, one vote," but the marketplace works by "one dollar, one vote," and the dollars are not evenly distributed among the people. To increase equity, political compatibility, and correct long-term distributions of resources (which is not something markets do particularly well), it is therefore important at least to recognize some of the main external costs and benefits of alternative energy technologies.

In economic formalism, it is not correct to count employment as a benefit of any project: it is treated (and must be for theoretical consistency) not as a benefit but as one of the costs of production, in the form of wages, salaries, and benefits whose payment causes some other useful output to be foregone. The amount, duration, location, and quality of work provided by energy projects are nonetheless socially and politically important. Such projects can either increase or decrease total employment. Power stations, for example, are so capital-intensive that each GWe built destroys about 4000 net jobs by starving other sectors for capital [Hannon 1976]. In contrast, careful and detailed case-studies [Buchsbaum *et al.* 1979; Schachter 1979], confirmed by more aggregated calculations [Rodberg 1978; Brooks 1981:154-167], have shown that efficiency and soft-technology investments provide several times as many jobs per kW as power-station investments, but better distributed by location and occupation [Congressional Research Service 1978:212-219] and arguably offering more scope for individual responsibility and initiative. It is partly for this reason that many progressive U.S. labor unions (e.g. United Auto Workers, Aerospace & Machinists, Sheet Metal Workers) support a "soft energy path."

Another important consideration is the program's macroeconomic effects via spending patterns and interest rates. (Responding effects--how people spend the money they save by using energy more efficiently--are important to the job analyses.) In general, efficiency and soft-technology investments are counter-inflationary: once in place they provide energy services at little or no additional cost, regardless of the price of depletable fuels. The relatively

short construction time and fast payback of these investments also tends to reduce pressure on interest rates. Kahn *et al.* [1980] have shown explicitly that an electric utility in financial difficulties (Appendix A) can increase the present value of its cash-flow severalfold by cancelling long-lead-time plant construction and spending the money instead on efficiency/solar investments, which turn over money very quickly. The saving from those investments is not only immediate and continuous; it is also widely distributed throughout society rather than concentrated in a few industrial sectors or localities.

Efficiency improvements and soft technologies have very much lower and more manageable risks to occupational and public safety [Holdren *et al.* 1980] and to the environment generally [*id.*] than do competing nonrenewable sources, even with stringent controls. A combined strategy of efficiency and renewables offers a potent way of avoiding global climatic change [Lovins *et al.* 1981]. And if coupled with recognition of the economic realities of the utility and nuclear sectors and of the problems posed by the strategic arms race, such an energy policy is also the most effective means so far proposed of limiting or even reversing the proliferation of nuclear weapons [Lovins & Lovins 1980].

Other geopolitical implications of such a strategy are also important. For example, both directly and by example, it could strongly influence U.S. allies towards a more sustainable energy policy: such countries as Britain, France, West Germany, and Japan all turn out to be able to provide essentially all their energy services using presently available and cost-effective efficiency and renewable technologies [Lovins *et al.* 1981]. The attractions of such technologies for developing countries have been extensively documented [*id.*; Lovins & Lovins 1980]. The Office of Technology Assessment [1978] has noted [Congressional Research Service 1978:199-209] the special advantages of independence from fuel and technology imports. "Solar energy is the one energy resource which is reliably available worldwide"--generally in larger and more consistent amounts in most developing countries than in the U.S. [*id.*:204], and competing with far higher than U.S. fuel prices. The advantages of soft technologies for rural-based development, for integration with agriculture, and for simplified versions using locally available materials would be especially striking in developing countries [*id.*:208; Lovins *et al.* 1981]. One result directly relevant to U.S. security would be the partial relief of the Third World frustration and desperation which could otherwise serve as a breeding-ground for revolutionary doctrines.

Similar arguments apply within American society itself. Technologies which tend to improve distributional equity, which are equally available to persons of all income levels, which increase individual and community self-

reliance and self-esteem, and which by their appropriate scale allocate energy and its side-effects more equitably will all tend to reduce the tensions now leading to "energy wars" (pp. 26, 153). Technologies which are perceived to be relatively benign, whose impacts are directly sensible and understandable by ordinary people, and which are accessible to an accountable and locally responsive political process [Lovins 1977b] would increase the likelihood that political conflicts over energy policy (Chapter 2.1.2) would be settled peacefully. And technologies which can be evolved, refined, and selected largely by the processes of the marketplace, rather than by the technocratic mandate of an Energy Security Corporation and an Energy Mobilization Board, are more likely not only to respect our national pluralism and diversity but also to use national resources efficiently. To see the dangers of central crash programs one need look no further than the experience of World War II [Congressional Research Service 1978:310-329], when the War Production Board, despite great talent and effort, mandated industrial expansions and conversions "which we could not use and did not need," diverting precious resources from other uses where they were more urgently needed and failing to use efficiently the considerable capacities of many small manufacturers [id.:377].

A final consideration important for policy, though difficult to quantify, is the risk of technological failure. It is sometimes suggested that efficiency improvements and soft technologies are uncertain to succeed, and that reliance on them is therefore a risky gamble. On the contrary, such technologies are known to work. (They embody more often the technologies of the 1890s than of the 1990s: nearly a third of the houses in Pasadena, California had solar water heaters in 1897 [Butti & Perlin 1980]). The extensions and modifications that would benefit many of them are of a modest character unlikely to present any substantive engineering problems. And the enormous diversity of the technologies and of the policy instruments that can be used to implement them provides many fallback routes to reach the same goals. In contrast, it is conventional energy supply technologies whose success hangs on adventurous extensions of the present engineering art into wholly uncharted regions where success is far from certain--the conditions of stormy seas, the Arctic, fast-neutron fluxes, shale mining, corrosive hot brines, synfuel processing, outer-space industrialization. It is those same technologies that must overcome formidable sociopolitical obstacles against even longer odds. And it is again those same technologies which stake the energy future on technical, social, and economic breakthroughs far surpassing anything yet experienced.

Those who advocate even greater reliance on such technologies have already brought us the greatest collapse in industrial history: a nuclear enterprise

which, after the investment of enormous technical effort and hundreds of billions of dollars, finds itself with no vendor in the world that has made a profit on reactor sales, with at least fifty more reactors cancelled than ordered in the U.S. since 1974, and with a similar collapse of prospects throughout the world's market economies [Lovins & Lovins 1980]. This unhappy episode underscores the risks of underestimating the challenges of "big engineering" [Bupp & Derian 1978], assuming that capital markets will indefinitely ignore the bottom line, and neglecting the social realities that make it more difficult to achieve a plutonium economy than to insulate houses. Although it may at first glance appear that the "hard" technologies require merely continuing to do as one has previously done, while the alternatives require striking out into new territory, a pragmatic assessment of what is actually working tells the opposite story. The contrast between one set of technologies, failing to meet the test of the marketplace despite lavish subsidies, and the other, capturing the market despite discriminatory institutional barriers, could not be more complete. Efficiency and renewables are not only the line of least resistance but also the policy of least risk.

7.2.3. System integration issues.

A full assessment of inherently resilient energy sources must consider what opportunities and problems may arise as such sources are gradually integrated into an entire energy system, combining them with each other, with existing energy devices and networks, and with other infrastructure such as buildings and farms. Although such issues can become exceedingly complex, we shall highlight by illustration some of the possible forms of integration that can improve system economics.

We have already mentioned that renewable space-conditioning systems, especially those using passive solar techniques [Department of Energy 1980; California Energy Commission 1980], can be integrated with other features of a new or existing building so as to save materials and money. Attached greenhouses, for example, can provide most or all of a house's space heating, a frostproof site for a solar water-heater, a cheery "sunspace" that extends living space year-round, and a place to grow food in all seasons [OTA 1981; Yanda & Fisher 1980]. In such a building, simple plastic-composite sheets can be used to form freestanding water tanks, usable both for heat storage (as passive-solar "thermal flywheels") and for aquaculture. In one Cape Cod design, each tank pays for itself annually by its oil saving or its fish production, with the other function provided free. Some houses are now integrating food production with

water recycling or sewage treatment: water hyacinth treatment plants, now commercially available [OTA 1981], provide better water quality than costly and energy-intensive tertiary treatment plants, while sequestering heavy metals and providing a feedstock for producing methane fuel and fertilizer.

The opportunities for multiplying functions and saving energy and money are almost unlimited. A dairy farm in Pennsylvania, for example, like others in Europe, uses an anerobic digester to convert manure to an improved fertilizer plus methane gas. The methane runs a diesel generator which powers the farm (many such operations produce an exportable surplus). The generator's waste heat makes hot water to wash the milking equipment (some farms use it in pasteurizing). Waste heat from the washwater is then recovered and used to preheat the cows' drinking water so as to increase the milk yield. A further project now being pursued will integrate these functions with on-farm production of fuel alcohols from crop wastes, cascading process heat and sharing other infrastructure, then using the alcohols to run farm vehicles and to sell as an additional export. Another common form of dairy-farm integration is to heat the anerobic digester in the winter with waste heat from the milk chiller (a giant refrigerator, legally required in many states). This often boosts the methane yield so much that one farm's output can meet all its own energy needs --before efficiency improvements--plus those of six other farms. Still another common pattern integrates the wet or dried residues of alcohol distillation into the feeding cycle (the high yeast content makes it a premium, high-protein feed). The carbon dioxide from fermentation can also be sold to refrigerant or soft-drink companies or used to increase the food output of a greenhouse.

Similarly ingenious--and thrifty--cascading of heat through a series of tasks at successively lower temperatures is the principle of industrial cogeneration [Williams 1978]. This energy- and money-saving technology [Machalaba 1979] replaces two separate boilers--one in a factory and another in a power station--with one in common, producing process heat or steam with electricity as a byproduct. Three-fourths or more of the energy in the initial fuel is then harnessed, not just a third. Air-conditioning or desalination can be further byproducts [Diesel & Gas Turbine Progress 1973].

The same objective can be achieved by using for space-conditioning the low-temperature waste heat from a plant used primarily to generate electricity. Some such systems [Energy & Defense Project 1980:167-169] achieve about 90% overall energy efficiency, are designed at the scale of a single apartment house, and use standard automotive engines burning a wide range of liquid or gaseous fuels. Current prices are about \$10,000 for 15 kWe + 38 kWt [Popular Science 1981], making the systems attractive despite their limited lifetime.

Either kind of cogeneration--using low-temperature waste heat from a generator or using a topping cycle to make electricity before using high-temperature industrial heat--can also be used with renewable energy sources. For example, the medium- or low-temperature waste heat from a low-ratio optical concentrator (which can improve the economics of solar cells) can offer an additional economic credit for domestic space and water heating, as noted below. High-ratio optical concentrators to make high-temperature solar process heat can make electricity first, just as if the heat were from a fossil-fueled boiler. Such solar process heat is also well suited to increasing the yield of bioconversion processes, as Prof. Michael Antal of Princeton University has noted. Prof. Sven Eketorp (Royal Swedish Institute of Technology, Stockholm) is even exploring modernized steelmaking with charcoal from wood: with no sulfur, the steel is of better quality, and copious fuel gas is a free byproduct.

Still another integration opportunity arises where wood wastes are burned for industrial cogeneration--an increasingly common practice in the forest products industry. It appears possible to cascade process heat to produce methanol as a cheap liquid-fuel byproduct from some of the "junk" wood input. This could also be done in the kind of small (tens of MWe) wood-fired power station proposed for some northern states and eastern Canadian Provinces. Indeed, if properly sited, such plants could simultaneously produce, at much reduced cost, electricity, methanol, and space heat, thus replacing all three of the main local uses of oil. Such an arrangement, like industrial cogeneration, obviously increases the resilience of the power grid by adding a diverse, localized source that can operate in isolation. The increasing use of cogeneration in oil refineries also reduces possible spillover of electric-grid failures into the oil system. Proposed uses of solar process heat in enhanced oil recovery would offer the same advantage, and are encouraged by overlapping tax subsidies offered both for the oil recovery and for the solar components.

We have referred several times to the use of low-temperature waste heat in buildings without mentioning that this can readily be done not only at the scale of one or several buildings but of an entire town or city. This is commonly done in Europe, and especially in Scandinavia. Sweden, widely regarded as the leader in district heating technology, is in the middle of a ten-year program of converting all cities of over 100,000 to district heating (Stockholm will take twenty years). This process is using special institutional and technical innovations. The latter include highly insulated flexible pipes which can be laid relatively cheaply over large areas, even at low suburban densities, to carry pressurized hot water. (Steam systems are usually considered obsolete.) Many Swedish boilers providing district heating, with or without electricity, can burn a wide range of fuels, including municipal wastes and

wood chips. Cheap backup boilers are also commonly provided to ensure reliable service, and there is usually redundant pumping capacity. An experimental boiler at Enköping achieves extraordinary fuel versatility, with high efficiency and cleanliness, through fluidized-bed combustion. The Swedish District Heating Association has shown great foresight by recommending that new district heating systems be designed to be easily convertible to solar district heating later. Several solar district heating systems are in operation or construction, mainly in Scandinavia [Margen 1980; Gleason 1981, 1981a, 1981b].

Several analyses have found that solar district heating can cut the delivered cost of active solar heat roughly in half [Hollands & Orgill 1977; Office of Technology Assessment 1978]. An analysis of the physics involved [Lovins 1978:492] found that a large water tank, shared between tens or hundreds of dwellings, provides (in comparison with a single house's small tank) a large volume-to-surface ratio, hence low heat losses; has low marginal cost per unit of volume; and has a favorable ratio of variable to fixed costs. One can therefore afford to use several m^3 of storage volume per m^2 of collector area, rather than a ratio of typically 0.5-0.8 in single houses with quasi-seasonal storage, like the Saskatchewan Conservation House. The increased storage volume then provides true seasonal storage from summer through winter. This in turn provides a full summer load, improving annual collector efficiency. It permits further efficiency gains by separating the storage volume into different zones with the hottest water near the center and the coolest near the periphery: this improves collector performance and further reduces heat losses. Finally, true seasonal storage makes it possible to orient collectors east or west rather than towards the Equator with only a small performance penalty, simplifying urban retrofits. The net result of all these effects is a marked cost reduction, probably to levels well below the oil prices of a few years ago [Hollands & Orgill 1977]. Incorporation of solar ponds (Chapter 7.3.2) or ice ponds or both [Taylor & Taylor 1981] would cut costs still further, and would incorporate energy collection and energy storage into the same device.

People unused to thinking about the variability of renewable energy flows often assume that integrating renewable sources into the existing energy system, especially the electric grid, would make service less reliable because many renewable sources are intermittent, dependent on vagaries of weather. This intermittence is presumed to require full conventional backup (negating the renewable sources' ostensible capacity saving), or enormous amounts of energy storage, or both. In fact, as noted earlier, renewable sources even in a small geographic area tend to complement each other, and their interruptions are briefer, more predictable, and quantized in smaller units than the interrup-

tions of conventional sources by technical breakdowns, oil embargoes, strikes, etc. This has been borne out by detailed analyses [Kahn 1978,1979; Sørensen 1979; Diesendorf 1981; Systems Control 1980].

Indeed, viewed more broadly, the need for energy storage is a far worse problem in conventionally projected systems. Their reliance on extensive central electrification requires [Ryle 1977] vast amounts of very awkward and costly electrical storage. In contrast, with economically efficient energy use, electrical demand would be so greatly reduced (Appendix A) that the grid would be dominated by present and small-scale hydroelectric supply, permitting storage in the form of water behind dams at no extra cost. (Kahn [1978,1979] notes, however, that in such a system the optimal ratio of the dams' peak output capacity to their impoundment volume may well change.) Liquid fuels store themselves. Heat storage for days or weeks, in rocks, molten salts or metals, etc. is straightforward [Office of Technology Assessment 1978] and not unduly costly--given efficient use. In short, an economically efficient combination of investments in energy productivity and renewable supply can reduce the energy storage problem from the intractable levels which reliable service would demand if present policies were pursued. The storage which would be needed in a soft energy path would tend to be relatively dispersed and invulnerable.

The most complex integration issues, extending well beyond traditional reliability considerations, arise with electrical systems--both because of the need for grid synchronization and because electricity, being generated and used at essentially the same instant, requires rapid regulation to ensure a balance between fluctuating demand and fluctuating supply. Hardware is moving so much faster than analysis that we already have attractive dispersed electrical sources (such as cogeneration, microhydro, and wind), and shall soon have more (such as competitive solar cells), before we know how best to use them. There is a legal framework--notably the Public Utility Regulatory Policies Act of 1978--encouraging the interconnection of such sources and compelling utilities to buy back their surplus power at the utilities' own "avoided cost" [Promoting Small Power Production 1981], and specific technical arrangements for interchange are starting to emerge [Sun*Up 1981]. Some utilities [e.g. Southern California Edison Co. 1980] are already planning to put numerous renewable devices of their own onto their grid. Yet the optimal method of connecting and using these sources is not yet known. Should they be integrated with the grid, or isolated from it--providing local storage and operating end-use devices on low-voltage DC? This is still an open question.

Some previously controversial issues have recently been settled: for example [Systems Control 1980,1980b], by showing how to ensure the safety of

utility personnel working on grid sections that might be energized by dispersed sources during a grid failure; or why such sources will not damage the grid or disturb its proper regulation; or how to avoid feeding damaging harmonics into the grid. But much more fundamental theoretical and practical questions remain. While such devices as DC-to-AC inverters have been used for decades to connect DC sources to the grid, and some of America's cumulative total of six million wind machines have been grid-connected, merely having feasible methods for interconnection is not the same as knowing which methods are best where.

This question is far more complex than may at first appear, partly because there are so many ways of interconnecting sources and grid [id.; Systems Control 1980]. Dispersed sources can generate electricity as low-voltage DC, e.g. using a fuel cell or solar cells or a DC generator, perhaps buffered by storage in a battery bank. The direct current can then be optionally converted to line-voltage AC using an inverter. This can be synchronized by the line voltage itself, by radio signals, or by the line voltage as processed through a microcomputer (perhaps the most versatile method); some inverters also produce approximately the correct frequency even if not connected to the grid. Alternatively, dispersed sources can generate AC directly using a synchronous or induction generator [Systems Control 1980:5-16 ff]. The former, the type used in large power plants, requires shaft rotation at a constant speed (3600 rpm divided by the number of pole pairs in the generator), but it can operate and can supply local loads in isolation from the grid. It can be connected with the grid only if its speed, voltage, and phase angle are first matched to those of the grid. Induction generators, on the other hand, must be driven slightly faster than the synchronous speed (otherwise they run backwards as motors), so they cannot operate independently of the grid, but they do not need to be synchronized before connection with it, and are simpler and cheaper than synchronous generators.

A further complication is that one must consider the source's relationship not only with the grid but with end-use devices. In general, electronics and some industrial processes, such as electroplating, require low-voltage DC and must currently obtain it by rectifying and filtering AC from the grid. Consumer electronic devices could be built cheaper and their weight and copper consumption considerably reduced if the AC-to-DC power supplies were omitted; given a market, such an option may become available. Motors, depending on type, may require DC, AC, or either*. AC is more common; some motors require it at fixed 60-Hz line frequency, while others, within limits, can operate from the "wild" frequency of an unregulated generator. (Some household wind machines use this system, but the generator can lock to grid frequency when connected to it.) DC

*Most household appliances, including e.g. washing machines, used to come in 32-VDC models matching widely used pre-REA wind machines.

motors, especially in small sizes, tend to be relatively scarce and expensive (military surplus is the traditional source), but inventors at NASA and elsewhere have developed plug-in solid-state "smart inverters," now entering the market for less than the incremental cost of DC motors, which enable standard AC motors to run very efficiently on low-voltage DC. Incandescent lights run on either AC or DC, given the right voltage. Fluorescent lights normally use 60-Hz AC, but new versions use their own AC-to-AC or DC-to-AC inverters to provide a high-frequency (400 Hz and up) output which boosts efficiency. (Hand-held fluorescent camping lanterns are of this type--hence their high-pitched whine.) An AC generator requires the least adaptation of standard household and office equipment but tends to encourage or even require grid integration whether it is economically optimal or not. A DC generator can operate DC end-use devices (such as most electronics) and connect to battery storage directly; can operate AC end-use devices through a small inverter, such as those commonly used to operate household appliances from car or boat current; and can connect with the grid via another inverter. Which approach is optimal will depend strongly on local circumstances, especially the proposed end-uses.

Although the technical problems of grid interface [Systems Control 1980] can be straightforwardly solved by hardware on or about to come on the market, most manufacturers have so far given too little attention to integration and "balance-of-system" issues. This is likely to be corrected as more solar-cell manufacturers begin to sell "packaged" systems including a range of power-conditioning, storage, control, and end-use equipment compatible with their solar-cell arrays. There is currently rather a narrow range of inverters on the market, and some common models, such as the Gemini™, were designed for wind machines and may not work well with solar cells. Better designs exist: Hitachi, for example, sells in Japan (but not in the U.S.) a chip-controlled inverter which digitally generates a 99%-pure sine wave and responds in a fraction of a cycle to any change in the size or reactance of the load. The Sandia experts who design inverters for U.S. nuclear weapons are also turning their attention to inverters for renewable energy sources. The market range of efficient, versatile inverters, including those amenable to remote control by utility signals, is therefore likely to increase rapidly in the next few years. This will not, however, be a complete solution to the broader problem of making sources, grid, end-user wiring and controls, and end-use devices fully compatible with whatever AC, DC, or hybrid systems emerge as standard.

The potential of dispersed renewables to reduce the vulnerability of the electric grid will not be fully realized if the rapid and somewhat hapazard evolution of grid-interface devices and system concepts continues to ignore

preparedness issues. Three issues stand out here. First, there is little effort at standardization, and different manufacturers may end up making incompatible equipment--restricting opportunities for improvisation and for moving equipment from one site to another in emergencies. Second, many preparedness options are being ignored: no thought seems to have been given, for example, to making DC voltages and hookups compatible with automobile electrical systems; providing accessible and foolproof terminals (and instructions) to facilitate such emergency interconnections with a car battery or alternator; designing grid inverters and controls to be resistant to EMP damage (p. 96); and encouraging designs which, without endangering utility personnel, can operate independently of the grid, serving local loads in isolation. On the contrary, present practice, to protect utility personnel in a way better achieved by isolation relays, encourages induction-backfeed generators and line-driven inverters--guaranteeing that if the grid crashed, renewable sources could not operate at all, even to serve local loads. Third, although current standards of grid reliability exceed any economically worthwhile value [Telson 1975], and relaxed reliability standards would improve still further the economics of intermittent renewable sources [Kahn 1978:338f], little thought is being devoted to seeking more sensible reliability standards better suited to heterogeneous needs*.

Dispersed renewable sources can prevent or mitigate cascading grid failures only if proper attention is paid at an early stage to how they are connected into it. The importance of these issues is emphasized in a major analysis of such sources' role [Systems Control 1980]. The study found [:5-50] that "There is no question that [they]...would have helped greatly [in the July 1977 New York blackout] provided that they had been properly integrated into the power system under conditions of cascading outage. This means that fail-safe procedures must exist to ensure that [the dispersed sources]...continue to function...and are, in fact, connected to the essential loads, e.g. buildings, government services, traffic lights, etc. Corwin et al....estimate that the economic loss caused by the disappearance of these essential services constituted roughly [83% of the direct losses in the New York blackout]....The total demand for essential services is estimated to be in the range of several percent of total demand. Thus, [in New York] several hundred megawatts of [dis-

*Uses requiring high reliability could get it more cheaply with local storage or standby capacity, as telephone exchanges, hospitals, etc. do now: it is cheaper to provide extra reliability in some places than maximal reliability everywhere as in the present grid. Similar considerations apply to voltage, frequency (p. 47), and phase stability. In an era of cheap digital electronics, it no longer makes economic sense to use the grid as a universal clock. Yet new turbogenerator designs are locking us into extremely stringent standards for decades to come, complicating the interface with renewables. If it turns out that phase and frequency stability need to be "stiffened" in a grid eventually dominated by large numbers of independent renewable sources, motor-generator sets with large flywheels might suffice: angular momentum is cheap.

persed sources]...might have prevented the loss of essential services." (It was the failure of traffic signals and street lighting which "facilitated looting, caused traffic accidents, and immobilized law enforcement.")

The analysis notes [:5-51] that "Although major restrictions affecting generation resources such as nuclear moratoriums, fuel embargoes, shutdown of all plants having the same design deficiency and strikes" have not been considered in past utility reliability calculations, they may be very damaging "because of the large number of generating units that could be affected simultaneously." If such disruptions caused the expected outage rate to increase from one day per decade to one week per decade, a standby source with an annual cost of \$60/kW could well be justified, because outage costs might well exceed its break-even point of \$11/kW-h [id.]. But for the dispersed sources to be "most useful during a supply emergency, it is essential that there is a priority load allocation scheme as well as supervisory control systems and other hardware to ensure that the system can, in fact, be operated according to this scheme. In the absence of priority allocation, essential loads might be curtailed while non-essential loads continue to be served. In addition, the [dispersed]...generator could easily be disconnected from the system by its overload, undervoltage, or underfrequency protections." Individual operators of dispersed sources might also need some way to limit their own loads to essential uses in order not to overload the isolated source; but then idle capacity available to the user might not get into the rest of the grid in its moment of need [:5-52]. This implies still another unconsidered design requirement in the control systems for dispersed renewable sources. Although Systems Control, Inc. has a continuing DOE research project on priority load allocation for entire grids, such measures are very far from realization, and virtually no work has been done on priority load allocation on the scale on which a small renewable source might be used and controlled.

In summary: adequate means of integrating all available renewable systems into the electric grids, and other parts of the energy system, are available. Further analysis and action are urgently needed, however, to determine which methods are best, whether end-use systems should be modified to reduce total costs, and how to design and organize the dispersed sources for greatest benefits to energy preparedness. Otherwise, as the soft technologies emerge into widespread use with unexpected speed, their patterns of use may evolve so haphazardly that many of their potential resilience benefits may be foregone.

7.3. The state of the art.

The immense diversity of appropriate renewable sources and hybrid combinations of them, their range of complexity and technical sophistication, and the extremely rapid pace of their development make any assessment of their technical and economic status ephemeral. An early review [Lovins 1978] drafted in November 1977 needed half its data changed by March 1978, and another quarter had become obsolete by the time the proofs arrived in May. This moving target, however, is generally moving in a favorable direction--either lower real costs or a lower rate of real cost escalation than nonrenewable competitors--so not being completely up-to-date may just mean omitting recent good news.

7.3.1. Economic status of soft technologies at the margin.

As Chapter 7.1.1 showed, economic comparisons are fraught with pitfalls. It is especially risky to compare data calculated by different analysts, because they may use different accounting conventions or degrees of conservatism. The assessment just mentioned [Lovins 1978], for example, whose economic results are summarized on the following two pages, used consistent conventions, and ensured that the conclusions were weighted against renewables by assuming:

- no real cost escalation for any source after 1976 ordering;
- generously low prices for nonrenewable systems [Lovins 1978a, 1979a];
- the same high fixed charge rate* for both types of systems (this discriminates against those with a high ratio of capital to operating costs, and allows no credit for renewables' shorter lead time and faster payback time [Kahn et al. 1980]);
- no cheap designs (such as passive solar systems, solar ponds, community-scale or roof-integrated collectors, collectors made of such materials as plastic films or extrusions, other low-technology designs and devices);
- for heating applications, an unrealistically efficient heat pump (250% efficient on the coldest winter day) operated by baseload (rather than average or peaking) electricity.

Such multiple conservatisms help to ensure that the severalfold price advantage shown for the soft technologies over their marginal competitors is not an artifact of arguable assumptions but a robust and decisive conclusion--one on which many analyses have lately converged [Stobaugh & Yergin 1979; Southern California Edison Co. 1980; Sant et al. 1981; SERI 1981].

*This converts a capital cost to an annual capital charge. The rate used--12%/y in real terms, or ca. 20-24%/y nominal--means that if a system costs \$1000/kW to build, \$120/y in capital cost must be charged against the output from each kW of capacity.

Table 1 Approximate marginal capital investment for complete energy systems delivering 1 bbl/day [~67 kW(t)] enthalpy to US consumers^a

Energy system	1976 \$/ (bbl · day) ^b	Form supplied ^c
Hard technologies:		
Traditional direct fuels, 1950s-1960s ^d or direct coal, 1970s	2-3,000	F
North Sea oil, late 1970s ^d	10,000	F
US frontier oil and gas, 1980s	10-25,000	F
Synthetics from coal or shale, 1980s	20-40,000+	F
Central coal-electric + scrubbers, 1980s	170,000	E
Nuclear-electric (LWR), mid-1980s ^e	235,000+	E
Technical fixes to improve end-use efficiency:		
New commercial buildings	~3,000 ^f	HE(?)
Common industrial & architectural leak-plugging; better home appliances	0-5,000 ^f	HE
Most heat-recovery systems	5-15,000 ^f	H
Bottoming cycles; better motors ^f	20,000 ^g	E
Worst-case, very thorough building retrofits	30,000 ^f	H
Transitional fossil-fuel technologies:		
Coal-fired fluidized-bed gas turbine with district heating and heat pumps (COP = 2), early 1980s	30,000 ^f	H
Most industrial cogeneration, late 1970s ^g	60,000	EH
Soft technologies:		
Passive solar heating (<100%)	< 0-20,000 ^f	H
Retrofitting 100% solar space heat, no backup needed, ~100-unit neighborhood	~20-40,000 ^{f, h, i}	H
Same, single house, mid-1980s	~50-70,000 ^{f, i}	H
300°C solar process heat, 1980j	120,000	H
Collection and bioconversion of farm and forestry wastes to fuel alcohols, 1980	<15-25,000+	F
Pyrolysis of municipal wastes, 1980	30,000 ^k	F
Microhydroelectric plants ^l	30-140,000	E
Solar pond and Rankine engine ^m	120,000 *	E
Wind-electric plants ⁿ	~70-185,000	E

^aData derived in (2) chapters 6-8; see also chapters 1, 3, except as noted in footnotes g, h, i, and m and conservation costs [derived from a wide range of literature, partly cited in (2)].

^bEmpirical data except synfuels (projected), fluidized-bed gas turbine (price of turn-key offer), and solar neighborhood heating (footnote h).

^cF = fuel, E = electricity, H = heat.

^dNot marginal; included only as baseline for comparison.

^eFor details, see (2) chapter 6. Briefly, assumes 1.1-CW(e) LWR ordered in 1976, at a price of \$585 per net installed kW(e) (1974 \$; Bechtel data) converted to \$929 (1976 \$) with the Bupp & Trettel current-dollar index of 1.26/year. Real escalation after 1976 assumed to be zero. Marginal fuel-cycle, transmission, and distribution facilities priced respectively at \$61, \$69, and \$420/kW (1974 \$; Bechtel data), converted to \$76, \$86, and \$525 respectively (1976 \$) with the 1.25 Marshall & Stevens Equipment Cost index. As-

Table 1 (Continued)

sumes front-end cost of \$100/kW (1976 \$) for initial core. Total investment, \$1,716/kW(e) installed, converted to \$3,120/kW(e) sent out by dividing by 0.55 nominal capacity factor, then to \$3,495/kW(e) delivered = \$234,500/(bbl · day) enthalpy delivered by surcharging 12% for equivalent 10.7% losses in transmission and distribution. These data are generally conservative (too low). Omitted costs include marginal capital investment in land, reserve margin, federal regulatory and security services, federal R&D, future services (waste management and decommissioning), and end-use devices; allowance for real cost escalation after 1976 (presently about 20%/year for LWRs and 7%/year for coal stations); the 6.5-8% of output needed to operate the fuel cycle; and all externalities and dynamic net-energy considerations. Including realistic estimates for all terms (except the last two and end-use devices) might raise the total to >\$5,000/kW(e) delivered.

^fIncludes the often high cost of end-use devices. An unpublished 1976 Shell analysis calculates typical investment per bbl/day used of the order of \$120-200,000 for a European car, \$35,000 for a conventional house heating system, \$5-10,000 for industrial boilers, and \$14,000 for a blast furnace.

^gCalculated from the review by G. N. Hatsopoulos, T. F. Widmer, E. P. Gyftopoulos, and R. W. Sant, *A National Policy for Industrial Energy Conservation*, published by Thermo-Electron Corp. (Waltham, MA), 22 April 1977. Assumes that both topping and bottoming cycles use both process heat and electricity inside the plant, avoiding marginal investment in electric distribution facilities.

^hEstimated from following entry and (55), with extra allowance for heat distribution in fairly low-density settlements.

ⁱAssumes that, in accordance with economic priorities, stringent heat-conservation measures have been applied first. Assumes traditional flat-plate collectors (not integrated into building fabric) with sensible heat storage in water in ~\$25/m³ tanks of modular concrete slabs (70). For cloudy high-latitude sites (e.g. Scandinavia), add about 40% to upper values. See (2, 68) and discussion in text.

^jRetail price \$118/m² (7) for 315°C, 0.44-efficient Winston collector; installation price \$22/m². See also text.

^kExcludes investment credit for byproducts (e.g. materials recovered) and for waste disposal services replaced. Much lower costs are possible: specific investment for Tatom's mobile pyrolyzer (text, footnote 14) is approximately five times lower.

^lBased on unpublished draft estimates by CEQ, MITRE, and New England Regional Commission [3-1,200/kW(e) installed with average capacity factor ~0.6-0.7], 5% distribution loss, and zero marginal transmission capacity (owing to old lines still available at old dam sites). See Huettner, J. 1978. *Situa, Potential and Problems of Small Hydroelectric Power Development in the United States*. Unpublished report to President's Council on Environmental Quality, Washington DC, 66 pp.

^mPond costing \$10/m² with 0.65 efficiency; Rankine engine plus local distribution (see text) \$800/kW(e); 10% engine efficiency (conservative, as the pond should yield 90-105°C, not 80°C); 4% distribution loss; 0.95 capacity factor using heat storage in pond. Land cost not included. *

ⁿUpper value from Risager 22.5-kW(e) machines, lower from run-on Schachle 3-MW(e) machines, at \$760/kW(p) and \$205/kW(p) respectively (1978 \$; see text); deflated to 1976 \$ with 0.87 index; for both, 0.3 capacity factor, 4% distribution loss, and a third of the ~\$380/kW <600-VAC distribution investment assumed marginal. Storage investment omitted, based on fuel- or water-tower operation in a hydro-peaked grid (see text). Ten-hour storage—sufficient (117) to make a typical Danish wind machine into a reliable source of firm power as a typical US LWR—might add about \$180-230 per kW(e) sent out to capital cost and have 20-30% losses. In practice it is very doubtful such storage would be needed. See B. Sorensen, *The Regulation of an Electricity Supply System Including Wind Energy Generators*, preprint for Second Int. Conf. on Wind Energy Systems, Amsterdam, 1978; and E. Kahn, *Reliability of Wind Power from Dispersed Sites: A Preliminary Assessment*, Draft Rep. No. LBL-6889, Lawrence Berkeley Laboratory, April 1978.

Table 2 Approximate prices of delivered energy from various US energy systems^a

Type	System	1976 (\$/GJ) ^b	1976 \$/bbl crude oil equivalent ^{b, c}
Raw fuels ^d	natural gas	1.9	11
	coal	2.1	12
	no. 2 fuel oil	2.8	16
	propane	4.4	25
	taxed regular gasoline	5.3	31
Space heat	electricity	8.7	51
	improved end-use efficiency ^e	-0.2-1.4	-1-8
	100% solar (neighborhood) ^f	1.2-2.5	7-14
	natural gas ^{d, g}	2.8	16
	no. 2 fuel oil ^{d, g}	4.1	24
Process heat	100% solar (house) ^f	2.9-4.1	16-24
	high-BTU syngas ^h	5.0-6.4	29-37
	LWR/heat pump ⁱ	7.4	43
	LWR/resistive ^k	17.5	101
	coal ^{d, l}	2.8	16
Fluid fuels	high-BTU syngas ^{h, i, l}	6.2	36
	300°C Winston solar ^m	7.3	43
	bioconversion ⁿ	1.4-4.8	8-28
	microhydroelectric ^o	1.7-8.0	10-46
	solar pond and Rankine engine ^p	6.9 *	40 *
Electricity	wind ^q	10.5-17.2	61-100
	LWR ^k	17.5	101

^a Illustrative values based on Table 1 and assumptions noted below.

^b Marginal prices except as noted in footnote d; capital investments converted to capital component of energy prices at 0.12/year fixed charge rate, which is high (therefore unfavorable to renewables) for the constant-dollar accounting used here, bearing in mind that utilities' income tax on revenues from marginal investments is generally zero or negative (171).

^c Equivalent crude oil at 5.8 GJ/bbl converted at 1.0 First Law efficiency; e.g. in practice (footnote g) the LWR/heat pump system would compete with $543 \times 0.7 = \$30/\text{bbl}$ oil (neglecting refining).

^d Approximate average of US regions (not weighted by consumption) at end of 1976; not marginal but shown as baseline. European prices tend to be much higher.

^e Aggregation of categories in Table 1.

^f Assumes average US insolation (180 W/m² averaged over all states of the earth's rotation and orbit); for cloudy high-latitude climates (e.g. Scandinavia), add about 40% to higher values. Assumes extremely energy-efficient buildings retrofitted with insulation and recuperators before solar system. Mid-1980s solar system installed price \$100/(m² + m³) and storage 0.4-0.5 m³/m² collector for single house. Lower prices are possible with innovative collectors or new buildings. Assumes 10¢/GJ for operation and maintenance (O&M).

^g Fuel price as above; free furnace with 0.7 First Law efficiency and 2% O&M charge. ^h Assumes gas system capital cost \$40,000/(bbl · day) delivered, working at 90% capacity factor; 57¢/GJ minemouth coal converted at 56% efficiency with operating costs (less byproduct credits) of 10¢/GJ and same delivery cost in free pipelines; no water constraints; combustion as in footnote g.

Table 2 (Continued)

ⁱ Higher value assumes that furnace and pipeline are assigned marginal capital costs of 28¢ and a conservative 95¢ per GJ respectively. Gas prices shown are probably $\geq \$1/\text{GJ}$ too low.

^j Electricity price from footnote k; \$200/kW(e) heat pump with an average and winter peak COP that equals 2.5 (exaggerating the probable capacity saving by a factor of 2.5, since most heat pumps have a COP of approximately one and add resistance heaters on the coldest days); 2% O&M.

^k Fuel-cycle cost at empirical burnup (credited for initial core), O&M, and taxes for station conservatively assumed to be 7.2, 1.5, and 0.4 m\$/kW-hr respectively; 6 m\$/kW-hr for O&M on transmission and distribution capacity. Delivered electricity price, 63 m\$/kW-hr, is conservative for reasons explained in Table 1, footnote e, and because non-nuclear (e.g. peaking) plants, allegedly inferior in the merit order, would produce even more expensive electricity. Present electricity prices are typically somewhat below this level in industrial countries, several times it in many developing countries.

^l Assumes \$8,000/(bbl · day)-fuel-used furnace with 0.8 First Law efficiency and 2% O&M. Coal price from top of table is current, not long-run marginal.

^m Assumes (Table 1) installed price \$140/m², with 180 W/m² average insolation, 0.44 First Law efficiency, 2% O&M, and 50¢/GJ buffer storage (including its losses as an equivalent surcharge). Highly selective flat plates or tubes—especially with a roof replacement credit—would probably be cheaper.

ⁿ Marginal collection and operating costs \$0.5-3.6/GJ net output.

^o Lower values characteristic of sites with existing dams; higher, of derelict or run-of-the river sites.

^p Assumptions as in Table 1, footnote m, plus 4% O&M. The capital cost of the engine [\$673/kW(e)] is close to the 1978 Kinetics Corporation price deflated to 1976 \$ (~\$700; see text) and well above prices expected for mass production (27). *

^q Range of capital costs from Table 1, adding 4% O&M and 10 hours of storage at \$50/kW(e)-hr. The storage cost component is \$6.3/GJ. Wind electricity integrated into a hydro grid (Table 1, footnote n) is therefore around the \$4.2-10.8/GJ range.

References to Tables

(2) = [Lovins 1977b].

(7) = [Grimmer & Herr 1976].

(55) = [Hollands & Orgill 1975].

(68) = Lovins, A.B. 1977: letter of 17 March to H.A.

Bethe, reprinted at 486-492 in U.S. Senate, Select Committee on Small Business & Committee on Interior & Insular Affairs, Alternative Long-Range Energy Strategies, 2 vols., USGPO.

(70) = [Fischer et al. 1976]

(117) = Sørensen, B. 1976: "Dependability of Wind Energy Generators with Short-Term Energy Storage," Science 194:935-937.

(27) = [Office of Technology Assessment 1978].

*The efficiency assumed for the pond in these tables is probably too high by a factor of about two, according to more recent results. The price should be about \$11.5/GJ (\$67/bbl) (4.1¢/kWh), but would be up to a factor of three higher if salt had to be trucked to the site.

Such generic analyses, though informative, cannot completely substitute for a more "microscopic" analysis that takes account of the complexities of system integration. Several recent studies, for example, have examined the engineering and economic details of adding dispersed renewable sources to a conventional power grid. While the shape of that grid is determined by certain unrealistic assumptions (notably that central power stations are far cheaper than they are at the margin, and that electricity demand will not decrease in response to rising real costs), this conservatism makes the favorable findings all the more interesting. The analyses [Systems Control 1980, 1980a, 1980b, 1980c; Boardman et al. 1981] find, for example, that dispersed renewable sources of electricity, even if intermittent, would improve the system's generation reliability [1980:5-52], and may add to service reliability by protecting the end-user against both grid and generation failures [:5-53]. Wind turbines (studied only as DOE designs, 200 kW-2.5 MW), photovoltaics, diesels, and fuel cells "can provide an economic alternative to large-scale central generation [assumed to cost much less than actual marginal cost] if their projected cost goals can be met." [1980:Summ:3] (Those goals have already been exceeded by small wind machines [Lovins 1978], and are likely to be met ahead of schedule, as noted below, for photovoltaics.) Roughly half the distributed sources' economic advantage comes from their capacity savings [Diesendorf 1981], half from their energy savings. The total cost savings is not very sensitive to the details of the utility's load or generation mix, but declines as the renewable fraction increases* (if the economic responses which would reduce total demand and change the shape of the grid [Diesendorf 1981] are assumed not to operate).

Spreading the renewables, e.g. wind machines, over a larger geographic region, or integrating different sources, e.g. wind with photovoltaics, improves their reliability and economics [System Control 1980:3-4; Diesendorf 1981; Kahn 1978]. Year-to-year variations in solar and wind energy are "less than the variation in water flow of many hydroelectric projects" and can be handled by similar planning methods. Dispersed sources, if reliable, can save transmission and distribution costs and losses (amounting to about a tenth of the generation savings) [id.:3-4]. Although analysis of renewable systems with

*A recent calculation [Lee & Yamayee 1980] suggests that under pessimistic assumptions, extra spinning reserve requirements may limit the economic use of some renewables to a few percent of the total load [Systems Control 1980]. But since the assumed methodology appears to treat renewable and nonrenewable generation asymmetrically (the latter should also incur such a penalty, especially since it can fail in much larger blocks) and to use unrealistic cost and outage data for nonrenewable sources, this conclusion cannot be considered reliable. Also, 1 kW of system storage "can provide up to 2 kW of spinning-reserve and load-following capability" [Systems Control 1980c:14], potentially providing a cheaper solution. Systems Control is checking this further.

dispersed storage is complex, system economics do not seem very sensitive to whether or where storage is provided, and photovoltaics in particular do not require on-site storage for favorable economics [Systems Control 1980c] as some critics have claimed.

Such detailed assessments offer useful insights into system design. But their complexity and opacity may obscure the broader relationship between the marginal prices of energy services from soft and hard technologies. The tables on the following three pages seek to illuminate that relationship in each of four service categories--low- and high-temperature heat, vehicular liquid fuels, and electricity--by assembling a list of documented price calculations for a wide variety of sources. All prices are normalized to the same units (constant 1980 dollars per million BTU or, approximately, per gigajoule) and to the same fixed charge rate (10%/y in real terms, or about 20+%/y in nominal or current-dollar terms). Although no such comparison can be definitive, that provided here is designed to show the main components that determine price--like the tables on pp. 230-231 [Lovins 1978] but using more up-to-date data.

The first table, for example, shows that low-temperature heat provided by burning today's fuels in a 70%-efficient furnace (better than most) will cost, with the very temporary exception of natural gas pending its decontrol, around \$15/10⁶ BTU, or about twice as much as [subsidized] average 1980 electricity used in an extremely efficient heat pump. Synthetic gas from coal is no better; marginal electricity is about the same or worse--\$25/10⁶ BTU in resistance heaters, \$10 with the same super-efficient heat pump. In contrast, efficiency improvements cost typically \$0-3/10⁶ BTU saved (maximum \$5 among the measures shown, which should keep the nation well occupied for the next decade or two). Passive solar measures are similarly cheap. With careful shopping, active solar heat, even on a single-house scale, is in the \$8-10/10⁶ BTU range, competing with deregulated fuels and power today. The real price of conventional packaged active systems is widely expected to continue falling by 2-3%/y [SERI 1981:II:175], and some simplified designs shown, whether do-it-yourself or commercial, have already dropped prices even faster, empirically achieving about \$4-6/10⁶ BTU even with commercial fabrication. The empirical cost (\$9) of heat from a municipally operated solar pond in Ohio (a technology described below) also competes with oil or electric-resistance heat at today's prices, and competes even with electric or gas heat pumps at marginal prices. Community solar heating systems [Gleason 1981, 1984; Taylor & Taylor 1981], using conventional collectors or solar ponds, can drop heat prices down into the range of passive solar or of the costlier efficiency improvements--about \$4-6/10⁶ BTU. For this application, then, presently available renewable sources are the best buy after efficiency improvements.

Illustrative delivered prices (1980 \$) for energy in various final forms, assuming a uniform 10%/y real fixed charge rate.

technology	remarks	reference	\$/10 ⁶ BTU
<u>Heat <100°C (<212°F) (35% of U.S. delivered energy needs) (excludes tax credits unless otherwise noted).</u>			
10/80 pre-decontrol gas	subsidized fuel & power	[SERI 1981:II:96]	4.0
#2 htg. oil @ \$1.10/gal	prices for comparison;	[Green 1980]	13.7
propane @ 80¢/gal	70%-eff. free furnace	[Green 1980]	13.4
el. @ 5.5¢/kW-h	free resistance heaters		16.1
el. @ 5.5¢/kW-h	\$250/kWe 250%-efficient heat pump, 1% O&M		6.8
marginal syngas (Lurgi methanation @ \$36/bbl oil price & 50% equity)	70%-eff. free furnace \$300/kWt input, 130%-efficient heat pump [Ross & Williams 1981: 306], 2% O&M	[Congr.Res.Serv. 1981; T&D from Am.Gas Assn. 1977 with GNP deflator]	15.0 9.0
marginal nuclear electricity @ 8.4¢/kW-h	free resistance heaters el. heat pump as above	see el. table below " " " "	24.7 10.3
thermal retrofits: direct-fueled houses	3%/y real discount rate, 10-y time horizon saving >50% of heat saving >75% of heat	[SERI 1981:II] [:12-13]	2.7 5.0
el.-htd. houses	saving >50% of heat	"	5.0
commercial bldgs.	saving >35% of h&c	[:70]	1.3-2.2
new houses saving >90%	Leger, Phelps, etc. (see text pp. 183-4)	[Leger & Dutt 1979; Shick, Shurcliff 1980]	<0
residential solar retrofit		[SERI 1981:II:94,204-5]	
passive	"best buys"	"	1.5-2.2
	"average" (DIY & Solar I)	"	3.5-7.8
active	"best buys"	"	8.2
	"average" (DIY & Solar I)	"	9.5
1980 typical commercial packaged solar water ht.	no tax credit	[:186-7]	9.4-32.5
	40% tax credit	"	5.6-20.4
1990 ditto, expected	no tax credit	[:186-7, 175]	5.0-25.5
1990 expected gas & oil	75%-eff. furnace, low prices	[:187]	12.9-25.1
ca.1982 Teagan solar w.h.	simple design	[Popular Sci.1981a]	ca. 6-7
1980 breadbox water ht.	batch; 10-y lifetime	[Green 1980; see also Shapiro 1980]	2.2-6.2
1978 site-assembled active-solar air system	[see also SERI 1981: II:172; Godolphin 1981]	[id.; Worcester Poly. 1978]	4.1-11.4
1990-2000 low-cost-collector program goals	average installed h.w. system	[:177]	5.3
inflatable greenhouse	10-y horizon, 8¢/kW-h fan	[Solar Flashes 1980]	ca.0.6
wood @ \$70-90/cord	20 MMBTU/cord, 50% eff.	[Green 1980]	7.0-9.0
solar pond (Miamisburg, Ohio muni. operation)	observed cost	[Soft En. Notes 4(1):18-20 (1981)]	9.2 8.0
community solar systems	flat-plate	[Schurr et al. 1979:Ch.II]	3.8-6.4
	concentrator		5.1

Illustrative delivered prices (1980 \$) for energy in various final forms, assuming a uniform 10%/y real fixed charge rate.

technology	remarks	reference	\$/10 ⁶ BTU
<u>Heat >100°C (23% of U.S. delivered energy needs) (all tax credits excluded except subsidies to nonrenewable sources).</u>			
marginal el. (8.4¢/kW-h)	free resistance heaters	see el. table below	24.7
\$40/bbl residual oil	[80%-efficient free boiler, 2% O&M		8.7
syngas as above			12.0
manure biogas		500 ft ³ active vol. [OTA 1981:99]	7.8
gas from \$30/odt wood (retrofit gasifier)		30%/y nominal fixed charge rate [OTA 1980:II:138]	3.4-3.7
same, \$20/oven dry ton	different assumptions	[SERI 1979:I:29]	3.8
30'dia. parabolic dish (new materials cost)	Doug Wood (Fox Is. WA) (av.US cond'ns 50% better)	[Soft En.Notes 2:97 (Dec.'79)]	2.2
300°C Winston, 44% eff., incl. storage (50¢/GJ)	180 W/m ² insolation, \$190/m ² inst'd, 2%O&M	[Grimmer & Herr 1977]	9.8
1980 handmade troughs, incl. storage (\$1/GJ)	\$45/ft ² , 60% eff. in New Mexico/New Hampshire	[SERI 1981:II:623, 630]	6.4-12.5
mass-prod'n goals	conservative (same range)	[id.:634]	3.7-6.9
	expected " " "	" "	3.2-5.6
	optimistic " " "	" "	2.3-3.8
Sandia 1985 projection	<315°C (<600°F)	[En. Insider '80a]	10.0
mass-produced Fresnels, \$28-57/m ² , 63% eff., incl. storage (\$1/GJ)	180 W/m ² insolation, install'n & plumbing \$60/m ² , 2% O&M	[Ross & Williams 1981:331; OTA 1978]	3.6-4.5

Vehicular liquid fuels (34% of U.S. delivered energy needs (all tax credits excluded except subsidies to nonrenewables; all BTUs counted as equal in value, which underestimates fuel alcohols' value in appropriate blends or engines)).

1980 taxed reg. gasoline	\$1.35/U.S.gal.		11.2
synfuel (EDS process, \$36/bbl oil, 50% equity)	\$4/bbl refining, marketing, & distribution	[Congr.Res.Serv.1981]	10.0
synfuel (H-coal, ditto)	(almost certainly too low an estimate)	[id.]	10.9
synfuel (Sasol II, ditto)		[id.]	22.7
gasoline saving	efficient road vehicles	see text pp. 186-7	<3.5
portable pyrolyzer	free, half-wet sawdust	[Tatom et al. 1976]	1.0-1.4
methanol from muni. wastes		[Green 1980]	3.9-8.1
pyrolysis "oil" from municipal wastes		[Benemann 1977]	6.0
homemade ethanol	no crop or labor cost	[Amer.Homegrown Fuel]	5.7
pyrolysis "oil" from wood & cellulosic wastes		[Green 1980]	6.9-12.6
ethanol from same @ \$11.25/odt	enzymatic process (estimated from lab.)	[Pye & Humphrey 1979]	ca.10-11
methanol from Canadian forestry wastes	hybrid processes	[InterGroup 1978]	ca.10-13
ethanol from grains	convent'l lg-scale dist'n	[OTA 1980:II:165]	11.3-15.7
ditto	ditto	[SERI 1980a:84]	15.8
ethanol from cellulose	ditto, projected	[OTA 1980:II:173]	12.2-17.0
methanol from \$10-30/odt wood, oxygen-gasified		[id.:140]	11.5-22.8
ethanol from lignocellulose	Emert process, projected (other processes in development may yield ca. 6-10)	[SERI 1981:II:581]	ca.16
methanol from all sources mostly from wood		[SERI 1981:II:591]	8.7-22.8

Illustrative delivered prices (1980 \$) for energy in various final forms, assuming a uniform 10%/y real fixed charge rate.

technology	remarks	reference	\$/10 ⁶ BTU
<u>Electricity (8% of U.S. delivered energy needs)(excludes all tax credits except subsidies to nonrenewables).</u>			
1980 av. price (5.5¢/kW-h)	subsidized	[Lovins 1981a]	16.1
NYC taxed av. price (15.3¢) (peak rate 24.9¢)		[Russell 1981]	44.8
marginal price from	subsidized; GNP deflator	[id.; Bowring 1980]	24.6
LWR commissioned 1988 (8.4¢/kW-h)	applied to earlier calculation (at 12%/y real fixed charge rate)	[Lovins 1977, 1978a, 1979a]	
same, recalculated (7.6 ¢/kW-h with 1979 reactor ordering or ca. 8.6¢ with 1981 ordering)	updated data on reactor, decommissioning, fuel-cycle, and O&M costs; updated grid & fuel-cycle-facility costs; GNP deflator used 1979-80.	[Komanoff 1981] (10%/y real fixed charge rate throughout)	22.2-25.2
using same methodology [Lovins 1977, 1978a, 1979a]		[Bechtel data: Lovins 1979a:nn20,21]	
electricity savings	typically 0-1.5¢/kW-h (see text, pp. 185,188)	[Appendix A; SERI 1981]	0-4.4
microhydro (2-8¢/kW-h)	highly site-specific	[SERI 1981:II:958]	5.9-23.4
homemade solar-thermal-electric (30' dish) (new materials cost only)	Doug Wood (Fox Is. WA) (3.2¢/kW-h)(av. US conditions are 50% better)	[Soft En. Notes 2:97 (Dec.1979)]	9.3
high-tech solar-thermal-electric (power tower) in Phoenix (7.4¢/kW-h)	\$85/m ² heliostats (\$96 falling to \$68 is expected in mass prodn.)	[SERI 1981:II:941-3]	21.7
same, dish design (ca. 16¢/kW-h)	1985, no cogeneration credit	[Solar Thermal Rpt.'81] [SERI 1981:II:943]	46.9
same, 1990 projection	25,000/y prodn. (5.2¢)	[id.]	15.2
10-kWp Millville wind machines, privately owned, 13 mph @ 40', 1% O&M added, no grid costs, free land	mass prodn. (5.1¢/kW-h) + innov. installn. (4.1¢) + 95% learn'g curve (3.4¢) (all based on empirical installed prices)	[id.:191]	14.7 12.0 10.1
2.5-MWp Boeing Mod II high-tech wind machine, + \$85/kWp land (\$3000/acre @ 5-dia. spacing), 0.3 capacity factor, O&M \$15,00/y	projected 100th-unit price with GNP deflator to 1980\$ (\$809/kWp net installed + 10% contingency), \$100/kWp T&D cost, 4% T&D losses (delivers @ 4.46¢/kW-h)	[id.:935-39]	13.0
community photovoltaic cogeneration system, municipal-util. owned, counting heat credit	\$15/Wp cells 18% eff. @ 28°C; \$80-135/m ² ; diesel backup, 1976-80 GNP deflator (6.4-7.2¢)	[Ross & Williams 1981:170-9]	25.1-28.3
best present photovoltaic components if assembled into cogen. system with waste heat worth \$13.7/MMBTU (same as \$1.10/gal oil in 60%-eff. furnace)	\$7/Wp, double for balance of system incl. 3x Winston concentrator, Phoenix-Seattle cap. factors (0.26-0.13), 4 kWt waste heat/kWe: thus 1.8-22.7¢/kWe-h	[Henry Kelly, pers. commun. 1981]	5.3-66.5
1986 silicon cells (DOE goal) or ca. 1983 Ametek est., no cogeneration	system \$1.6-2.2/Wp, util. buyback @ 50% of av. price (delivers @ 5.9-8.1¢/kW-h)	[Russell 1981; DOE 1980a; JPL 1980; Ametek 1979]	17.3-23.7
1990 photovoltaics (11¢)	Southern Ca. Edison est.	[Ca. Energy Comm. 1980a:176]	32.2
Martin-Marietta PV/Fresnel 1981 technol. @ 50 MWe order		[Maycock 1981:42]	17.6

The second table shows a similar result. Synthetic gas burned in an industrial boiler to provide process heat will deliver even costlier heat (\$12/10⁶ BTU) than residual oil at market prices does now (\$9), though still cheaper than marginal electricity (\$25). Even expensive wood wastes can deliver the same clean heat via commercially available gasifiers [OTA 1980:II:154-5; SERI 1979] for \$3-4. Simple solar concentrators at temperatures adequate for nearly all industries other than ceramics/bricks/glass and primary metals (which need higher concentrations or indirect forms of solar energy [Lovins et al. 1981:82]) now deliver heat at prices competitive with syngas or OPEC oil or both*. Homemade versions (costing only materials, not labor) can achieve \$2 in cloudy areas. As the prototype concentrators now on the market are replaced by mass-production models [Solar Thermal Report 1981b], prices over the next few years should fall to about \$3-6--well below present oil prices--through normal scaling-up of what are now model-shop operations. (If coal cost only half as much per BTU as OPEC oil does today, a clean coal boiler could probably not compete with most mass-produced solar concentrators. Average U.S. coal prices--for big orders in areas with a coal-delivery infrastructure--are somewhat below that level, but long-term coal prices will probably seek opportunity-cost levels against world oil.)

Many renewable liquid fuels--especially those from thermochemical processes fed with farm or forestry wastes--are likewise cheaper than coal synthetics. This is partly because woody materials have much more favorable chemical reaction kinetics than coal: they break down faster, at lower temperatures, and with little or no tar formation. Both the energy and the capital requirements are accordingly lower, and the yields generally higher, than for equivalent coal liquefaction. Some renewable liquids, especially those emphasized by current policy, are slightly costlier per BTU if inefficiently produced or if made from specially grown crops, though the comparison shown does not count the credit due to fuel alcohols for their cleaner and more efficient burning properties. Methanol can be especially efficient in a high-compression engine, such as a spark-ignited diesel. A methanol-powered cross-country flight by former Astronaut Gordon Cooper and by President Reagan's former pilot [Cooper & Paynter 1981] not only dramatized methanol's potential for greatly improving the airlines' parlous finances; it also demonstrated that in piston engines above about 10,000', methanol is more powerful per gallon than aviation fuel.

Finally, the table on p. 236 shows that a wide range of renewable sources--microhydro, wind, simple solar-thermal engines, even some photovoltaic cogeneration systems--can deliver electricity at about 2-6¢/kW-h. This competes

*An Israeli entrepreneur is building 5000 m² of parabolic troughs in Israel in 1981, and plans more in the U.S. in 1982; he offers to supply up to a conservative 30% of industrial steam loads 10% cheaper than a factory now pays, and he pockets the difference. [Avram Kalisky, pers. comm., 1.81].

handily with the marginal delivered price from newly ordered central power stations (ca. 8¢). Many of the presently available renewables also compete with the present average (rolled-in) price seen by the consumer, or with the roughly equivalent fuel and operating cost of running oil-fired stations (5-7+¢). Virtually any of the renewables would be attractive today in high-price areas, such as New York City (15¢ regular taxed price and 25¢ at peak periods in late 1980), Alaskan villages and remote military bases (typically upwards of 40¢/kW-h), and rural areas of developing countries (30-90¢/kW-h). The table shows that the smaller technologies tend to deliver cheaper electricity than the centralized ones (Chapter 5), and illustrates the diversity of options. Photovoltaic prices, as noted below, are dropping so quickly that DOE now expects them, even in central-station applications, to compete with average grid prices by 1986 using demonstrated technologies [Adler 1981; Maycock 1981; Russell 1981]; but microhydro and wind, and perhaps other renewable sources, have already achieved this with hardware now on the market. The same cannot be said of the centralized solar-electric systems—multi-megawatt wind machines, power towers, ocean-thermal-electric conversion, centralized biomass plantations to fuel thermal power plants, solar satellites, etc.--to which much of the Federal solar budget has been devoted for the past decade. There is not even a credible prospect of ever achieving such competitiveness via the fusion program, the second-biggest component of DOE's R&D budget (with about half as much FY1982 funding as fission and twice as much as all renewables combined).

7.3.2. Selected technical developments.

The state of the art in inherently resilient energy sources has been treated in detail in recent literature for lay audiences [Energy & Defense Project 1980], for scientists [Sørensen 1979; Lovins 1978], and for policy-makers [SERI 1981; Soft Energy Notes]. It is not possible in a document of this length to do justice to those fundamentals. Rather, in this section we shall highlight some recent technological advances which seem especially promising for making the U.S. energy system less vulnerable and which have not been described in earlier sections.

Heat. Passive solar techniques are now known to be the best buy (after, and in combination with, efficiency improvements) for both new buildings and retrofits. Sophisticated design tools [DOE 1980] and packaged design kits tailored to particular climates [California Energy Commission 1980] have become available. One can now accurately simulate and optimize the performance of any combination of passive elements in any climate on a standard hand calculator (thanks largely to a Los Alamos effort now threatened with discontinuation). In general, such techniques have turned out to be much simpler and more effective than expected. Rule-of-thumb techniques have developed which make it hard

to go wrong. Annual national and international passive-solar conferences have refined and propagated these techniques with remarkable speed. Successful passive solar houses are now being built or retrofitted [Reif 1981] even in the least favorable solar climates [e.g. Maine Office of Energy Resources 1980; Woychik 1981].

New materials with very unusual properties are becoming available for both passive and active solar use. For example, an adhesive selective surface selling for \$1.2-1.9/ft² (SunSponge®) boosts the performance of Trombe walls (glazed solar-absorbing masonry walls) by about a third, but costs less than the equivalent level of movable insulation (ca. R-9 to R-12). Transparent insulating and heat-reflecting materials (including Heat Mirror®) are now in commercial production. Some new plastic-film glazing materials, such as 3M's Flexigard®, transmit better than window glass at visible wavelengths, are nearly opaque in the infrared, and show no signs of degradation after 12 years' weathering in bright sunlight [King 1979]. Tough, highly durable plastic films have been proposed by T.B. Taylor and developed by Brookhaven National Laboratory as materials for active solar collectors at least ten times cheaper than conventional ones. Such collectors have for several years been sold in Switzerland [Ener-Nat 1979], and could easily be site-assembled just as plastic-film greenhouses are now. Stockpiling appropriate films and instructions could indeed be an important element of any solar mobilization.

So diverse are solar collector designs that it is not yet clear whether flat-plate or concentrating collectors are superior for low-temperature applications. OTA [1978] found that the cheapest collector on the 1977 market (other than rollable plastic mats and other unconventional designs, some of which are quite effective) was a concentrating parabolic trough. Very simple automatic tracking mechanisms have been developed. They can be quite reliable, as attested by the performance of military and airport radar trackers. Robert Carlson of Sandia, who has sold thousands of sets of plans for a homemade concentrator of the type used on his own house, argues with some justification that even in a climate as cloudy as Boston, the extra efficiency of a concentrating collector when exposed to direct sunlight can more than make up for its inability to capture the diffuse light which a flat plate can, since much of the diffuse light arrives at too low an intensity to reach the operating threshold of a conventional flat-plate collector. This argument has particular merit for photovoltaic cogeneration systems (below).

A counterargument, however, is that in a cloudy climate, "conventional" flat plates--those with a flat-black absorbing surface--are the wrong choice. A "selective" surface, which absorbs visible wavelengths well but radiates

infrared badly, is far preferable. A selectivity ratio (visible absorptivity : infrared emissivity) of about 5 can be obtained simply by brushing a lampblack-water slurry on a metal absorber plate and letting it dry to a thickness which removes the metallic luster but is still gray, not black. A selectivity of ca. 8-10 can be achieved by many kinds of electrochemical coating processes and some special paints. Alternatively, for $\$3/\text{m}^2$, a selectivity-8 foil can be applied, e.g. by stretching it over a slightly convex collector. This simple modification produces remarkable results [Raetz 1979, 1979a]. Because the diffusely scattered light on a cloudy day, although somewhat reduced in intensity, is still energy of extremely high quality--its effective color temperature is over 5000°F --a selective surface, suitably insulated, will attain very high equilibrium temperatures. Thus Raetz's selectivity-8 single-glazed collector heats domestic water by a highly satisfactory 54°F with 45% efficiency on a cloudy winter day in Hamburg (total insolation $200 \text{ W}/\text{m}^2$, or one-fifth of the full summer-sunlight level). (Insolation of $300 \text{ W}/\text{m}^2$ raises the efficiency to 57%.) Higher selectivity makes the collector even less sensitive to cloudiness. A selectivity in excess of 50 can be obtained by sputtering thin films, using well-established high-vacuum techniques similar to but less demanding than those used in coating optical lenses. A selectivity-50 surface in a hard vacuum will serve a process heat load at $500\text{--}600^\circ\text{C}$ (ca. $930\text{--}1110^\circ\text{F}$) on a cloudy winter day in Juneau. If the liquid-metal coolant in such an absorber should stop flowing, the metal absorber plate would melt.

In contrast, only direct sunlight can be used to operate conventional concentrating dishes, such as the 23'-diameter General Electric prototypes which recently supplied 750°F (450°C) at 71% efficiency [Sunworld 1980]. (That temperature is adequate to supply essentially all process heat needs in the food, paper, and chemical industry, plus most of the needs of oil refining.) Point-focus systems for loads up to about 1500°F are beginning to enter the market. Power Kinetics Corp. (Troy NY) offers a $\$37,000$, 80-m^2 , 59-kWtp, 74-79%-efficient dish with calculated Northeast payback times of 3-10 y against oil [Barden 1981], similar to the "conservative" SERI mass-production goal on p. 235. Another dish has heated gas to 2200°F (1204°C) steadily, and to 2600°F (1427°C) maximum [Solar Thermal Report 1981a]. Commercial line-focus systems, of which over $100,000 \text{ m}^2$ were made in the U.S. in 1980, go up to ca. 500°F . Central receivers with fields of tracking mirrors (heliostats) are under development (an Italian firm sells small fields [OTA 1978]) and can achieve temperatures adequate to vaporize any material. Some potentially very cheap concentrators substituting micropolished reflective plastic films for metal are evolving at SERI, Lawrence Livermore Laboratory, and elsewhere. Cheap dish concentrators have also been homemade [Soft Energy Notes 2:97 (1979)], including one which, in the Olympic Peninsula, provides 40 kW of steam at a new-materials cost less than half the cost of heat from burning 1981 OPEC oil at 80% efficiency.

Among the most rapidly emerging solar technologies during 1980-81 is the solar pond, a passive device for cheaply supplying heat year-round, day and night. Although there are several types of solar pond, the most common is a hole in the ground with an impervious liner, filled with concentrated brine--various kinds of salts can be used--and preferably with a darkened bottom. Both direct and diffuse solar radiation heat up the bottom of the pond, but because the hotter water there dissolves more salt and is thus denser, convective heat transfer to the surface is suppressed. (With some geometries, the salt can also form a self-stabilizing gradient of optical bending power which helps to concentrate light on the bottom.) A layer of fresh water on top, which stays fairly well segregated, acts as a transparent insulator. Other forms of translucent insulation can also be added. A simple heat exchanger, such as some pipes near the bottom, can extract heat at nearly the boiling point: solar ponds in sunny areas can boil by late summer. The large thermal mass of the pond provides built-in heat storage, although it may take some months to come up to its full working temperature. Good ponds are 20-30% efficient in converting total insolation to heat. They may cost \$5-10/m² if salt is available on-site, as near many mines and factories; \$30/m² or more if the hole, liner, and salt must be specially provided.

Solar ponds were originally expected to work only in desert climates, but the successful operation of a 2000-m² pond by the City of Miamisburg, Ohio since 1978 has dispelled that notion. Even with ice on the surface, the bottom temperature in the cold spell of February 1978 was still 83°F (28°C). Total cost, mostly salt (1100 tons) and liner, was \$34.4/m², maintenance cost is very small, and the delivered heat price, as noted on p. 234, is \$9.2/10⁶ BTU, equivalent to 75¢/gal oil in a 70%-efficient free furnace or to 3.1¢/kW-h electricity [Wittenberg & Harris 1980; Nielsen 1980]. Solar pond research being pursued by the Jet Propulsion Laboratory, Los Alamos, California Energy Commission, Southern California Edison Co., and others should lead in the next few years to the sort of "cookbook" understanding of pond design already obtained for passive solar techniques. Solar ponds are a robust, nearly invulnerable heat source: even an event which disturbed the salt gradient and reduced collection efficiency would still leave weeks' worth of recoverable heat. Similarly, ice ponds [McPhee 1981a] provide full seasonal storage of coolth, offering reliable air-conditioning at a tenth of the usual energy cost.

Vehicular fuels. Enough liquid fuels can be sustainably produced from farm and forestry wastes (not special crops) to run an efficient vehicle fleet [SERI 1981; OTA 1980]. This will require careful management and, most likely, basic reforms of cultural practice which are in any case essential to protect soil fertility [Jackson 1980]. Primers on biomass liquids have been published elsewhere [SERI 1981; OTA 1980; Energy & Defense Project 1980; Lovins & Lovins

1981]. The main types are pyrolysis "oil" made by heating woody substances with little air; such "oil" slurried with char produced in the same process; methanol; ethanol; butanol; and blends of various alcohols. (Gasohol® is a blend of 10% anhydrous ethanol with 90% gasoline.) Some of these fuels are usable directly in unmodified engines; others require minor modification which costs up to several hundred dollars for retrofit or nothing at the factory. It would be helpful for preparedness if, for example, car makers used methanol-proof components in fuel systems, and provided carburetors with a switch for easy conversion between gasoline, gasoline/alcohol blends, and pure alcohol.

Excellent manuals on commercial ethanol production from crops are available [SERI 1980,1980a], though so far similar material is not available for other, more promising, feedstocks, processes, and products. Extensive grassroots training programs in ethanol still construction and operation are provided by a wide range of groups, especially in the Midwest [Energy Consumer 1980]. Given that knowledge, a still big enough to run a car can be built from commonly available materials in a few days and operated from almost any sugary or starchy feedstock. Although not energy-efficient, it does provide a premium fuel from what may otherwise be waste materials. Small- and medium-sized ethanol plants offer interesting advantages for integration into farm operations [Patterson 1980] and are attracting special interest as a community economic development tool at small Black colleges [Billingsley 1980]. Whether ethanol is produced in small stills or (preferably) a wider range of fuels is produced by more efficient methods from non-crop feedstocks (especially cellulosic wastes), the potential contribution, both routine and emergency, from many small plants could be very large. As an analogy, in the U.S. about 11 million cows in herds averaging 60 cows produce 15 billion gallons of milk per year--about a fifth as many gallons as the gasoline used annually by U.S. cars. Yet that milk production "is efficiently supplied by small-scale decentralized operations." [Hobson 1980]. Likewise, "The average stripper well produces about 2.8 barrels of oil per day, which is about one-seventh of one one-thousandth of a percent of what we consume in oil every day,...but...the cumulative effect of all our stripper wells [is]...21% of continental oil production." [Hallberg 1981]. Moreover, alcohol production based on farm and forestry wastes would tend to be concentrated in the rural areas which have disproportionate needs for mobility fuels [Hallberg 1980], which are at the end of conventional supply lines, and which cannot export food to the cities without adequate fuel. It is for this reason that Admiral Moorer, former Chairman of the Joint Chiefs of Staff, noted "the valuable contribution of a highly dispersed, self-contained liquid fuel production system to serve the vast U.S. farming community in developing the strategic defenses of the United States" [Holmberg 1981].

Many people think only of corn-based ethanol when biomass liquids are mentioned. In fact, this is far from the only important feedstock, process, or product, and--especially with the inefficient, oil- or gas-fired stills commonly used--is among the least attractive. Other processes, notably thermochemical ones, have better economics and at least equal technical simplicity. (John Tatom [4074 Ridge Rd., Smyrna GA 30080] has designed effective pyrolyzers for developing countries, made of old oil drums, rocks, and pieces of pipe.) Feedstocks abound, even in urban areas: just the pure, separated tree material sent each day to Los Angeles County landfills, not counting mixed truckloads, is 4000-8000 tons with an energy content of the order of 1 Gwt. At a nominal conversion efficiency of 70%, and assuming a source term of 1 Gwt, the resulting fuel yield--equivalent to the energy content of nearly half a million gallons of gasoline per day--would suffice to drive a 60-mpg car more than ten miles per day for every household in the County. The cotton-gin trash in Texas is enough to run every vehicle in Texas at present efficiencies. The distressed grain in Nebraska would fuel a tenth of the cars in Nebraska at 60 mpg, and at the same efficiency the straw burned in the fields of France or Denmark each year would fuel every car in the country. Feedstocks range from walnut shells and rice straw in California to peach-pits in Georgia and apple pumice (left after squeezing cider) in Pennsylvania. But numerous small, localized terms add up to enough--including logging wastes--to fuel an expanded U.S. transport system at cost-effective levels of efficiency [SERI 1981].

Technical developments in providing cost-effective biomass liquid fuels are of three main types. The first, most important, and least supported is reform in farming and forestry practice to make these activities sustainable by protecting soil fertility while at the same time providing residues for fuel conversion [Lovins & Lovins 1981; Jackson 1980]. This is an intricate biological, social, and economic question which no Federal program begins to address; but without it, Americans will not long remain able to feed themselves. The second is the improvement of processes to ferment sugars or starches into ethanol. For example, a few years ago it took 50-100,000 BTU to distill ethanol to 190°PR. Today some commercial processes use 25,000 to go all the way to anhydrous ethanol [BioSynthetics 1981], and the best demonstrated processes have reduced this to 8-10,000, using advanced distillation or critical-fluid processes [Ferchack & Pye 1981]. Innovative water-alcohol separation processes include freezing (New England applejack and Appalachian moonshine were long fortified by leaving the kegs out to freeze), chemical extractants, hydrophobic plastics, cellulosic adsorbents [Ladisch *et al.* 1978], and--just emerging--synthetic membranes [Ferchack & Pye 1981]. Good process efficiencies, in

weight yield from feedstock to alcohol, are now typically 0.46-0.48--90-95% of the theoretical limit--for glucose fermentation to ethanol. These processes are likely to become widely available at all scales of operation over the next few years.

The third and technically most exciting line of development is the evolution of new processes (or refinement of old ones--acid hydrolysis has been in use for over a century) to convert cellulosic wastes, the most versatile and abundant kind, into alcohols. Acid hydrolysis can break down cellulose to glucose with virtually complete yields [Ladisch *et al.* 1978], providing a yield of over 0.4 from cellulose to ethanol [Ferchack & Pye 1981a; SERI 1981]. Thermochemical processes can yield methanol by the routine catalytic "shift reaction" [SERI 1981:II:583ff] of synthesis gas (a hydrogen/carbon-monoxide mixture produced by oxygen gasification of biomass) with steam. Using modified coal-conversion technology, which is not optimal for biomass, the yield of the whole process is about 0.40-0.48 [OTA 1980]. A new downdraft gasifier has increased the methanol yield to an astonishing 0.83 [SERI 1981:II:585]. Pyrolytic "oil" production yields at least 0.5 [Lindström 1979], and typically 0.6-0.8 including the slurried char, even in small plants that can fit on the back of a pickup truck [Tatom *et al.* 1976]. Methanol has long been used as a racing-car fuel for its high performance, cleanliness, and safety; in a high-compression-ratio car (say, 14:1 or more), it can readily supply only 20-25% fewer mpg than gasoline, even though its energy content per gallon is only half as great. Methanol/ethanol/tert-butanol blends and other combinations can be even more advantageous [Tom Reed, SERI, pers. commun. 1980]. Since cellulosic feedstocks are the most widespread and the easiest to convert and use efficiently in small, dispersed plants using low technology, the emerging cellulosic conversion processes seem particularly advantageous for building a nearly invulnerable national capability for dispersed, sustainable liquid fuel production.

Road vehicles can be run on other than liquid fuels. Canada has a program of conversion to compressed natural gas (a method already used by some hobbyists) and to LPG*. A million portable wood gasifiers (p. 149) ran European cars during World War II. Extensive data are available [Ingeniörsvetenskapsakademien 1950] on their design and performance. Although they take about an hour a day to fuel and care for, and consume 22 lb of dry wood per gallon gasoline equivalent, they are such a robust substitute in heavily wooded regions that Sweden is considering stockpiling gasifiers in case of severe gasoline shortage. Other alternatives are conceivable: heat engines based on liquid air may be interesting, and electric cars, though uncompetitive in principle with efficient fueled cars, might become viable with very cheap on-car photovoltaics.

*About 3 million LPG carburetors have been sold in the U.S. since 1969.

Electricity. The most commonly discussed renewable electrical sources are microhydroelectricity, wind electricity, and photovoltaics (solar cells). Wind and microhydro can also be used for pumping water or heat, for compressing storable air to run machines, or even for refrigeration [Franklin 1980].

A little-known option may, in favorable sites, be the cheapest known source of new baseload electricity: a solar pond with a low-temperature (e.g. Rankine) heat engine, especially if it works into an ice pond as suggested by T.B. Taylor. Israel has operated a 150-kWe solar pond/Rankine engine since 1979; plans 5 MWe at ca. \$2000/kWe in 1983; plans 2 GWe in floating solar ponds in the Dead Sea by 2000; and projects 4-7¢/kW-h for a proposed Southern California Edison Co. plan (officially projected at 7-10¢) in the Salton Sea.

Small hydro--variously defined as less than 5-25 MWe or less than 100 kWe per site--is being intensively exploited by entrepreneurs [McPhee 1981]. All but forgotten until 1976-77 [Congressional Research Service 1978:48-128], innumerable small dams, including over ten thousand in New England alone, had been abandoned. (Many existing large dams were also left with empty turbine bays: id.:129-136].) The National Hydroelectric Power Study by the Army Corps of Engineers, due to be completed in autumn 1981, is reportedly identifying still more opportunities. Some sites are environmentally or institutionally unsuitable [Franklin Pierce Energy Law Center], but many others can be refurbished (and some developed from scratch) using straightforward and cost-effective technologies [Energy & Defense Project 1980:178-84] for which a do-it-yourself manual is available [Alward et al. 1979]. Run-of-the-river sites and heads as low as 5' can be used [Schneider Corp. 1980].

The rate of progress is hard to measure because many utilities seem to underreport their hydro projects: e.g., Pacific Gas & Electric and Southern California Edison reported 170 MWe of hydro in the January 1981 Electrical World survey of capacity additions underway, but the California Energy Commission's staff report on the proposed Allen-Warner Valley coal project lists, for these two companies respectively, 707 and 1150 MWe as "reasonably expected to occur" and ca. 1500 and 750 MWe as "additional, but not counted." Thus projects already underway, most of them with FERC permits filed for, total 1857 MWe--over ten times what the EW survey reflects [Jim Harding, pers.comm., 19 May 1981]. A further barrier is that the Federal Energy Regulatory Commission is inundated with license applications--2600 averaging 8 MWe in the two years ended July 1981--including some applications apparently filed by a few companies that intend to sit on them or resell them at "scalper's" profits. Nonetheless, the impact of microhydro is already locally substantial [McPhee 1981] and should over the next few decades approach the same magnitude as existing large-scale hydroelectricity--but far more evenly distributed around the country*.

*Sweden plans 250 installations by 1982; New Zealand has 60 and plans more [Gouraud 1981].

Microhydro should be speeded by new companies providing a "no-hassle" turnkey development service and by the imminent entry into the U.S. market of cheap Chinese turbines (designed by American engineers a half-century ago). China, as mentioned on pp. 49-50, now claims to get over 5.4 GWe from over 90,000 local microhydro sets (few of them grid-connected [Energy & Defense Project 1980:178]) ranging from 0.6 to 100 kWe, usually with 0-5 m heads. This adds up to at least two-thirds of all Chinese electricity outside the cities [Lovins 1977b:124], and powers over half of the dispersed light industry--an important element of Chinese civil defense planning.

Windpower has the disadvantage (compared to flat-plate photovoltaics) of moving parts, but the considerable advantage of high power density. A machine extracting 30% of the power in the wind--reasonable performance for a good design without fancy equipment (tipvanes, shrouds, variable pitch, etc.)--can extract 24 W per m^2 of swept area at an average windspeed of 4 m/s; 81 W at 6 m/s; 192 W at 8 m/s [Sørensen 1979a:6]. In contrast, a 10%-efficient solar cell in average U.S. insolation extracts only 18 W/ m^2 . Accordingly, a simple wind machine can capture mechanical work at very low prices. Simple designs like that mentioned on p. 152 and pp. 206-7 [Bergey 1981], or the \$1500 (1980 \$) homemade (est. \$6700 commercial) 17.5-kWp (@ 17 m/s) Chalk wheel of Otto Smith [Lovins 1978:496], are becoming available. The Borre sailing design [*id.*] is on the market as an 18-kWp model for about \$650-690/kWp (1980 \$) [Carter 1978], producing at about 5¢/kW-h (1980 \$). U.S. Windpower machines based on commonly available components are selling (complete except tower, FOB factory, 1981) for \$610-700/kWp in the 25 kW (model CA) and 37 kW (CB) sizes [Stoddard 1981], and a refined prototype can be made for about half that much [*id.*]. A private entrepreneur, Terry Merckham, recently built a 1-MWp machine for a Pennsylvania factory at a cost (materials plus labor) of \$400/kWp. The more than 40 manufacturers of small machines are listed in periodic indices published by Wind Power Digest, the American Wind Energy Association, and the Rockwell International wind test program at Rocky Flats. Basic guides to selecting wind machines [Park 1981] and their sites [Wegley et al. 1978] are bringing the technology into common currency. New "wind prospecting" methods include satellite observation of inversion breakup (U. of Alaska) and detailed computer simulation of windflow over digitized terrain (Lawrence Livermore).

Large-scale commercial wind projects are springing up. Southern California Edison Co., operating a 3-MW hydraulically coupled machine designed by Charles Schachle, has already contracted for 55 MWe of wind capacity from entrepreneurs and is negotiating for another 215 MWe. California expects to get 1% of its electricity from wind in 1985 and 10% in 2000: a 350-MWe windfarm 30 miles NE of San Francisco is to be built during 1983-89, to supply nearly 1 TW-h/y at 3.5¢/kW-h real, and U.S. Windpower is currently installing a 200 × 50 kWp array, with 600 machines to be supplying 90 GW-h/y by mid-1983. The same firm built 20 50-kW machines on Crotched Mountain, N.H., within five months of first

contacting the site owner, and hooked them to the utility grid in late 1980 in a mutually profitable symbiosis [Graves 1981]. Windfarms™ has contracted (subject to financing) to supply 9% of Hawaiian Electric Company's electricity by 1985 via 20 4-MW wind machines on Oahu. A private entrepreneur, Jay Carter, has reportedly built 125 sailing gyromills of 25-30 kW each, listing at \$18,000, to run a bleach plant in Dalhart, Texas [Energy Research Reports 1979].

Photovoltaics are extremely durable, reliable, and simple to use: when placed in the sun, they produce direct current, needing no maintenance unless they have a tracking concentrator. These qualities have long commended them for such applications as powering buoys, highway signs, Forest Service towers, microwave relay stations, and remote military bases (part of the rationale for proposed DOD purchases [Congressional Research Service 1978:223-274]). As with transistors in the 1950s and 1960s and integrated circuits in the 1970s, the cost even of conventional, first-generation cells (Czochralski silicon wafers) has been falling dramatically, with array prices dropping from about \$30/W

1976 to \$7-10/Wp in 1979-80. (Photovoltaics are rated in peak watts or Wp of direct-current output at 1 kW/m² insolation.) There is a consensus among the managers of the very competently run Federal program that implementing proven technologies for producing such cells in a more automated fashion, without the 30-odd hand operations now needed, can reduce the array price to \$2.80/Wp (1980 \$) by late 1982, corresponding to an installed whole-system price of about \$6-13/Wp for flat-plate systems [JPL 1980; Smith 1981].

It is also highly likely that several of the second-generation processes already demonstrated and in advanced commercial development--silicon web or ribbon growth, amorphous silicon films (which can be very cheaply vacuum-deposited on anything, including plastic films), or other materials--will achieve, on or ahead of schedule, the DOE 1986 array-price goal of \$0.70/W (1980 \$), corresponding to a whole-system price of \$1.60-2.60/Wp. Sanyo has already invested \$50 million in a factory for commercial production of amorphous silicon cells [Maycock 1981], and several firms have announced the development of amply efficient amorphous materials which they expect to market by about 1985 at about \$0.70/Wp or less. One such material, developed by AMETEK [1979], can be applied by a simple wet-chemical process similar to electroplating; is already about 8% efficient; has a materials cost of 40¢/Wp; and can be applied to the absorber plate of an AMETEK flat-plate solar heat collector to produce electricity as a byproduct. Collector glazings can also be used as nonfocusing concentrators by dispersing a fluorescent dye in the glazing material so that the fluorescence is internally reflected to a photovoltaic strip along one unshaded edge: a small cell area could thus produce byproduct electricity.

Detailed economic calculations show that the confidently expected 1986 prices, assuming no technological breakthroughs, will compete with grid electricity in most of the U.S. [Russell 1981]. Accordingly, DOE's Solar Photovoltaics Energy Advisory Committee stated in February 1981 that a combination of rapid technical advances, PURPA buyback provisions, and higher marginal cost estimates for conventional sources make it likely that central-station photovoltaics will compete around 1986 [Adler 1981]--which means that well-designed cogeneration versions should compete around 1981-82 on a residential scale and starting several years ago on a community scale [Ross & Williams 1981].

It will probably be fairly common for new houses (and some old ones) by the late 1980s to be net exporters of electricity. General Electric is developing photovoltaic shingles which cost about the same as normal shingles but produce electricity too and are hooked up by nailing them onto the roof. Texas Instruments is developing a clever photovoltaic-hydrogen system with onsite hydrogen storage and a fuel cell. Technical developments in this field are moving, as is the way of semiconductors, too quickly even to report. This puts an extra sense of urgency into our findings about the risk of utility bankruptcy (Appendix A) and the need to plan for the long-term shape of renewable source integration into the power grid (pp. 224-228 above). The photovoltaics revolution is indeed already upon us (p. 236). We had better start getting used to the idea and figuring out how best to use these rugged, almost invulnerable devices to increase the resilience of national electrical supply.

In summary, then: the most up-to-date surveys of the status of renewable sources find [e.g. SERI 1981] that cost-effective renewable technologies now in or entering commercial service are sufficient to meet at least most, and probably about all, energy needs of the United States within the lifetime of power stations now being commissioned. In conjunction with even more cost-effective efficiency improvements, these inherently resilient sources can profoundly improve national security by making impossible many types of large-scale failure of energy supply and many of the side-effects of failures in dangerous energy systems. These developments have so far received virtually no professional attention outside the relatively small number of energy specialists who have kept up with them. Yet they offer arguably the greatest national-security opportunity in our lifetimes.

The concluding chapter of this survey, therefore, seeks to pull together the threads of this analysis in order that those concerned with preparedness and resilience may be better able to grasp this extraordinary chance to turn a present danger into a new source of security and prosperity.

8. IMPLICATIONS FOR PREPAREDNESS

The foregoing Chapters have sought to show, generically and specifically, what makes the present energy system vulnerable; how to design a far less vulnerable system; and how in particular a combination of efficient energy use and appropriate renewables (properly built and interrelated) can achieve a high degree of inherent resilience while simultaneously minimizing the economic costs of providing energy services.

To date it has often been the economic benefits of this more resilient strategy, not its preparedness advantages, that have attracted notice, support, and action. While the specter of oil cutoffs is at the back of people's minds, the reality of day-to-day energy costs is at the front. The importance of reducing those costs is most visible not at a national level, where an oil-import bill of thousands of dollars per second is too big to visualize, but at a local level, where household energy bills are all too obvious. At a local level, moreover, the problem and solution can be stated in concrete and memorable terms, and specific opportunities for and obstacles to such a policy can be most directly identified and dealt with. Accordingly, for coping with energy disruptions or the threat of them, community-based action is the fastest and most efficient way to build a resilient energy system. Support for such local analysis and action--reinforcement of what is already a rapidly growing national trend--is our first and most important recommendation.

The reasons for this trend can be vividly illustrated by four recent local efforts to improve energy resilience: one arising from stark economic necessity, one from foresight and planning, and two from actual supply cutoffs. The first of these examples--an analysis of the needs of a local economy, and a political process giving substantive form to that analysis--comes from Franklin County, the poorest county in Massachusetts: cold, cloudy, economically depressed, and almost wholly dependent on imported oil. A group of citizens with a \$30,000 DOE grant several years ago drew on a range of community resources and participation to analyze the County's energy future [Pomerance et al. 1979].

They began with a dismal energy present. Every year, the average Franklin County household was sending out of the County more than \$1300 to pay for energy. At an informal "town meeting" to discuss the study's findings, someone held up a bucket with a hole in it, to dramatize the drain of \$23 million per year from Franklin County, mostly to Venezuela. That drain was the same as the total payroll of the ten largest employers in the County. (The total County energy import bill for all sectors was about \$48 million in 1975, rising in 1980 to \$108 million [current \$]--of which \$52 million was just for households.)

The analysts next showed that if the lowest official forecasts of energy needs and prices in 2000 became reality, people would become four times worse off, paying \$5300-odd per year (not counting inflation) to buy household energy from outside the County and, generally, outside the country. To keep that leaky bucket full, the biggest single employer in the County would have to clone itself every few years for the rest of the century. This prospect made the Chamber of Commerce and utility people blanch: the future, presented in such terms, was simply not possible.

The study group had, however, worked out what could be done instead: making the buildings heat-tight, using passive and active solar heat, running vehicles on methanol from the sustained yield of some unallocated public woodlots, and meeting electrical needs with wind or microhydro within the County. Local machine shops, with skilled workers unemployed, could make all the equipment. The cost of paying it off would be about the same the County was then paying for household energy--about \$23 million per year. But the leaky bucket would thereby be plugged up. The money, the jobs, the economic multiplier effects would stay in Franklin County, not go to Venezuela.

Before the 1973 oil embargo, a dollar used to circulate within the County some 26 times before going outside to buy an import; today, it circulates fewer than ten times. Franklin County is hemorrhaging money. A fair consensus developed, as a result of this analysis, that the only hope for economic regeneration would be to stop the bleeding by promoting local energy efficiency and self-reliant renewable supply. As a result, what was a paper study is now the Franklin County Energy Project. With various fits and starts--and considerably delayed by the sudden loss of its modest Federal funding--it is starting to be implemented. Once the energy problem was so presented that people could see it as their problem, and one not just of convenience but of economic survival, they were motivated to start solving that problem on their own. More recently, a broadly similar process has grown up in thousands of American counties, cities, and towns [SERI 1980b, 1981a]. The U.S. energy system is actually developing a measure of economic efficiency and preparedness, but largely from the bottom up, not from the top down.

A second example of local energy efforts arose chiefly from concerns about energy vulnerability rather than cost. Dade County, Florida is currently assembling a coherent Energy Contingency Plan [Leslie Brook, pers. commun., 18 May 1981]. Its first element, a Fuel Management Program, has not only contributed to preparedness--through efficiency in the 4600 County vehicles, establishing priorities, stockpiling to maintain essential services through several months' complete cutoff, and a wide range of other measures--but has set up more efficient accounting controls which have since 1973 saved the County more than 13

million gallons of motor fuel. The County's impressive energy management activities [MetroDade 1980a] include not only crisis-management measures but also efficiency/renewables programs designed to prevent crises from arising. When Federal contracting was recently frozen, Dade County officials were in the process of developing curricula and workshops to train other local officials in this broad approach to energy preparedness [MetroDade 1980].

While Dade County's analysis is neither as broad nor as deep as we have attempted here, its integration of preventive measures with crisis-management measures is a useful model for developing further the essential idea that energy preparedness consists of far more than having a paper plan for rationing gasoline. If Florida's energy supplies are seriously disrupted in the future, it is likely that Dade County--knowing how its energy is used and having well-established procedures in place for orderly maintenance of vital services--will be better off than most other areas. The County's motivation was in part the conviction, as the program's Deputy Director expressed it [Brook loc. cit.], that energy emergency preparedness "is a critical issue of national security and ought to be a top priority of the United States Department of Defense." It is heartening that some local officials are taking national concerns so much to heart--but it is hardly surprising in view of the tangible local benefits.

Such advance planning is still exceptional. The disruptions we described in earlier chapters are still the stuff of everyday life whenever several things go wrong at the same time. In the January 1981 cold spell, for example, schools and some businesses in several eastern Massachusetts communities had to close because a storm off of Algeria had sunk an LNG tanker on 28 December 1980 [Knight 1981], causing Massachusetts gas companies to deplete their stockpiles when pipeline capacity proved inadequate to import gas they had stored in Pennsylvania. Such incidents remain fairly common, and the only response local officials can make is curtailment: turn down thermostats, huddle over wood stoves, shut down factories, and listen to emergency broadcasts. Yet in some communities that have none of the access to sophisticated management and resources that might be expected in Massachusetts, actual energy shortages have already led to a remarkably effective response.

One such instance is fairly well known [Energy Consumer 1980b:23]: the improvisation of mesquite stoves and simple solar water heaters in Crystal City, Texas, whose natural gas supply was shut off in the late autumn of 1977 in a dispute over prices. Low income and the imminence of winter forced the townspeople to work with what materials they had. They did so well with weatherization and renewables that many are still using and indeed expanding those "stopgap" measures: responses developed expediently served to introduce people to energy options of which they had previously been unaware and whose economic advantages they then wished to receive routinely.

A less well-known and even more impressive case comes from the San Luis Valley in southern Colorado--a sunny but cold plateau at 8000' elevation, nearly as large as Delaware. The traditional Hispanic community in the Valley heated with firewood, cut on what they thought was their commons-land from old Spanish land-grants. A few years ago, a corporate landowner fenced the land and started shooting at people who tried to gather wood. The people thus had an instant energy crisis. Some of the poorest people in the United States, they could not afford to buy wood or any commercial fuel. But a few people in the community knew how to build very cheap solar greenhouses out of scrounged materials, averaging under \$200 each. Through hands-on greenhouse workshops, somewhat akin to old-fashioned barn-raisings, the word spread quickly. In a few years, the Valley has gone from a documented four to over 800 greenhouses--which not only provide most or all of the space heating but also extend the growing season from three months to year-round, greatly improving families' winter nutrition and cash-flow. There are solar trailers, a solar Post Office, even a solar mortuary. Baskin & Robbins has installed a high-technology solar system on its ice-cream parlor. Now other renewable sources are starting to spread: wind machines are springing up, and some farmers are building an ethanol plant fed with cull potatoes and barley washings and powered by geothermal process heat. The Valley is on its way to energy self-reliance because, under the pressure of a supply interruption, people found they were too poor to use anything but renewables.

Tools for such local action are becoming widely available: two national conferences on community renewable energy systems [SERI 1980b, 1981a], books of case-studies [Center for Renewable Resources 1980; Ridgeway 1979], how-to books [e.g. Wilson 1981; Reif 1981; Morrison 1979], guides to county energy analysis [Benson & Okagaki 1979], indices to local resources [Department of Energy 1980a], technical compendia on renewable resource bases [Glidden & High 1980] and technologies [Soft Energy Notes], and introductions to community planning for resilience [Corbett 1981]. Among the most valuable ways of putting tools in people's hands has been the free DOE periodical The Energy Consumer, whose special issues--on such subjects as solar energy [1979], alcohol fuels [1980], community energy programs [1980a], and energy preparedness [1980b]--include comprehensive state-by-state indices of key people and programs to help local action. In 1981, unfortunately, publication of The Energy Consumer and public distribution of its back issues were suspended and its staff was disbanded, so this effective source of self-help information was lost.

The number, diversity, and intensity of community-based programs for energy efficiency and appropriate renewable supply [SERI 1980b, 1981a] have led a few thoughtful citizens to propose the concept of a locally based "efficiency-and-renewables mobilization" to increase national energy preparedness. Chief

among these are Fran Koster (former director of TVA's solar programs and previously a prime mover in the Franklin County Energy Project) and Alec Jenkins, working in his private capacity (he is a senior staff analyst for the California Energy Commission) and as a Division Chairman of the American Section of the International Solar Energy Society (AS/ISES). Together they have organized (generally under AS/ISES auspices) several programs to explore voluntary "mobilization." This approach presupposes [Energy Consumer 1980b:13ff] that "energy shortages will not be half so politically disruptive if communities see a timetable and a supply of their own making," and that mobilization should seek to anticipate and prevent shortages, not merely respond to them.

The "mobilization" concept recognizes not only the political efficiency of locally based decision processes, but also the fact that in hundreds of communities and several regions (including New England and Southern New York State), assessments of local renewable resources have found "a gold mine of opportunity" [id.]. To this end, Jenkins and Koster and their colleagues have proposed to AS/ISES an institute to speed the dissemination of tools for local energy mobilization; are working with several existing efforts to train local government officials; have sought (so far unsuccessfully) DOE support for preparing a "mobilization handbook" for widespread local distribution; and are hoping to enlist industry as a major constituency and actor for promoting local initiatives. Jenkins is also preparing a paper summarizing the mechanisms, incentives, and organizational patterns that seem most effective in promoting community awareness and action to increase energy preparedness.

The remarkable chord that these citizen actions have struck rests on the widespread perception, especially among municipal and county leaders, that if, or more likely when, energy supplies are next seriously disrupted, Federal programs, with the best will in the world, will not be able to do much for most people; it will be every community for itself. People who want to forestall the resulting inconvenience or hardship can therefore be persuaded that their best protection is to get busy with efficiency and renewables--not things that others may do for them in ten years, but things that they can do for themselves now. Our analysis, based on meetings in hundreds of communities, has shown that this approach is indeed the most fruitful, for it responds both to people's well-founded anxieties about energy supply and to their equally shrewd suspicion that there is a great deal they can do to increase their personal and community energy security--given access to information*.

*This approach raises the question of what would happen if before or, more likely, during a crisis a great many people were to try to insulate houses, build greenhouses and stills, etc. simultaneously. Abbie Page at The MITRE Corporation in Bedford, Massachusetts is eager to explore where bottlenecks would arise in supplying materials, equipment, and skills, and how these snags could be avoided by preparedness planning. This next stage of analysis deserves FEMA's support.

In a country as large and diverse as the United States, any issue aggregated to a Federal level tends thereby to become all but unmanageable. Much of the current Federal trend towards devolving choice back to a state and local level wisely recognizes that unique local circumstances can often be best dealt with by people who know them in detail--provided the will to do so is there. In this spirit, existing state energy and emergency-planning offices could play a key role in energy preparedness, and a few are already doing pioneering work which deserves careful consideration by Federal officials.

California, for example, is widely regarded as the leader--perhaps just ahead of oil-dependent Hawaii--in analyzing and preparing for interruptions of oil supply (and to a lesser extent of natural gas and electricity). This approach and expertise are in part an outgrowth of the high expectation of a major earthquake and of state experience in managing drought. The state's oil prospects have been analyzed at a sophisticated level [Ca. Energy Commission 1981]. The Energy Commission's Energy Contingency Planning Staff, led by Commissioner Varanini, has summarized in a memorable 1981 wall-chart ("Oil Crisis Regulations") the labyrinth of present arrangements--international, Federal, state, and local--for coping with an oil crisis, and has shown in a 1980-81 series of well-argued papers and consequence models that those arrangements would be largely unworkable even if executed with perfect competence.

Energy Emergency Districts have been proposed [Energy & Defense Project 1980] as a basis for an inventory and mobilization of local energy sources and skills, and for demonstrating local renewable sources' potential for improving preparedness. The California effort, though generally supportive of the local "mobilization" concept and of other private initiatives, does not go nearly so far. It is still largely directed towards managing shortages, not with the more fundamental shifts in strategy needed to make the probability and consequences of shortages very small. Thus although the efforts of Varanini *et al.* are arguably the best of their kind at a state level, they are no substitute for the more comprehensive view of energy resilience proposed in this study. They can, however, help to provide a framework for political leadership to encourage and coordinate local actions that would most quickly accomplish that shift. It is therefore especially unfortunate that the same Federal budget cuts which crippled many local energy programs are also likely to lead to the dismantling, during 1981-82, of most of the state energy offices. In the absence of such proposed substitutes as the Energy Management Partnership Act (which was not enacted), much of the present capability for coordinating state energy preparedness measures [Energy Consumer 1980b:32-45] is slated to disappear. Such state efforts, like corresponding ones at county and municipal scale (e.g. in Los Angeles), should on the contrary be strengthened as the most cost-effective way to achieve local goals which in aggregate add up to national energy preparedness.

Federal rhetorical support for cost-effective efficiency improvements and appropriate renewable sources is nowadays abundant. Disagreements over their role are generally questions of degree. The Canadian Government's strategy paper [EMR 1980:65], for example, states that

The realities of the energy future indicate the wisdom of accelerated efforts to develop new and renewable energy forms....While most conventional forecasts imply a relatively modest role for renewables, it is clear that many Canadians do not share that view. Indeed, the dramatic surge in the use of [fuel]wood...suggests that these forecasts understate substantially the contribution to be made. Moreover, while forecasts are useful tools for analysis, they can tell us only what will happen under certain conditions. The conditions--the policies--are the keys. Many thoughtful and concerned Canadians believe that we should alter the forecast, that we should decide soon on a preferred energy future, and establish the conditions that will take us there. The National Energy Program envisages a much greater role for renewable energy. The Government of Canada believes that economic realities now favour a range of renewable energy options.

U.S. policy places greater stress on allowing the renewable share to be determined by the marketplace rather than by social planning, and the previous Administration's goal of 20% renewable supply by the year 2000 has been formally abandoned (current DOE estimates are under 10%--a share only a third larger than today). Many of the substantive embodiments of previous bipartisan commitments to accelerating efficiency and renewable technologies have also been diluted or reversed. Nevertheless, the general tone is guardedly supportive [DOE 1981a:9]:

Most 'renewables'...have little or no public opposition; nor do they pose severe long-term environmental problems. Thus, they are well suited (and may be confined) to any specific regional markets where they make economic sense. The Administration's clear and consistent adherence to free-market principles will remove artificial barriers and provide a major impetus to the development of such technologies.

In giving practical effect to such generalities, however, we recommend several shifts of emphasis, or correction of omissions, which would help Federal agencies to improve energy preparedness.

First, and perhaps most important, is to reflect in Federal energy thinking the comprehensive approach to vulnerability and resilience which the foregoing analysis has developed. This has not been done since at least World War II (if then)--even under such Secretaries as James Schlesinger, whose DOD/CIA background might have been expected to heighten his sensitivity to such issues. DOE's desire for a "resilient" energy policy [1981a:1] needs to consider a far wider range of disruptions than interruptions in oil supply--the traditional and continuing emphasis [:2]. Responses to vulnerability need to be broadened far beyond stockpiling, encouraging dual-fueling of certain oil-using devices, developing surge capacity, and international liaison [:13-14].

Currently, a few Federal programs do reflect specific security concerns. The Strategic Petroleum Reserve, for example, has benefited from vulnerability analyses (albeit without encouragement from DOE or much coordination with

FEMA); there are minor utility programs concerned with the integrity of regional grids and with traditional studies of technical reliability; and there are site- and program-specific nuclear security analyses. Yet the concerns of all these programs are akin to, and somewhat narrower than, those raised in Chapter 3. They do not yet reflect this study's broader approach to systematically achieving energy resilience. The potential contribution of end-use efficiency and appropriate renewable sources in enhancing national security--especially in minimizing the consequences of terrorist attacks--is thus not being properly exploited because it is not fully perceived.

Second, the Administration's free-market philosophy is long overdue and can produce immense benefits in efficient energy investment, but is not yet being consistently applied [Lovins & Lovins 1980a]. The resulting market distortions impede the use of resilient technologies. When the Assistant Secretary for Fossil Energy remarked (as reported in the 8 October 1981 Oil Daily) that without the \$1.5-billion Federal loan guarantee to Tosco, even its partner Exxon might pull out of a vast Colorado oil-shale project, that was tantamount to an admission that shale oil cannot compete in a free market. If so, it hardly deserves Federal support; conversely, if it can compete, it does not need support--the same approach being applied to efficiency and most renewables, which can hold their own in fair competition but perhaps not against things like subsidized oil shale, conventional oil, Alaskan gas, and central-station electricity.

From a preparedness perspective it is regrettable that recent budget shifts have tended to maintain or increase support to the costliest, most vulnerable, and most heavily subsidized technologies while reducing support to the cheapest, least vulnerable, and least heavily subsidized. Eliminating all the subsidies would be better. Meanwhile, compensatory programs (such as the Conservation and Solar Bank) to help the most vulnerable members of society achieve energy self-reliance deserve support. So do cost-effective Federal non-subsidy programs to speed the refinement and use of the most resilient technologies. A sampling of such opportunities--many already endorsed by DOE's Energy Research Advisory Board--includes industrial efficiency programs, appliance efficiency labelling and a wide range of other consumer information programs, analysis of institutional barriers to least-cost investments, the implementation studies and programs of the Solar Energy Research Institute and its regional branches (including, for example, research into the behavioral determinants of energy use [ERAB 1981:6]), and R&D into second-generation photovoltaics. The last of these is, like refrigerators, a prime example of a vast market likely to be captured by Japan if U.S. industry concentrates mainly--as it would tend to do if not helped to take a longer view--on first-generation technologies soon to be rendered obsolete.

Third, in order to make policy more coherent and direct it more towards achieving energy resilience as soon as possible, far greater efforts are needed to ensure the conditions that enable the marketplace to work efficiently. Price deregulation will indeed provide [DOE 1981a] even greater incentive for energy efficiency and renewables. But failure to remove market imperfections will result in a frustrating and persistent lack of opportunity to respond to price signals. For example, vigorous enforcement and strengthening of the Public Utility Regulatory Policies Act of 1978, which seeks to replace restrictive utility practices with a competitive market in generation, is the best single way to encourage entrepreneurial programs of dispersed electric generation. Yet the Federal Energy Regulatory Commission, rather than encouraging states to set full avoided-cost buyback rates, is overlooking derisory rates and defending the Act only weakly from legal and political attack by special interests that do not want to be exposed to competition. FERC is also rapidly increasing subsidies to central-station generation--effectively locking up money which, in an efficient capital marketplace, would go to cheaper and more resilient alternatives, greatly improving utilities' financial integrity (Appendix A). Likewise, most Federal programs to help states and localities to modernize their building codes, provide information on cost-effective technologies, and otherwise remove barriers to least-cost investment are being removed from the Federal agenda with little substitute in sight. The resulting Federal energy policy is not consistent with FEMA's preparedness objectives.

Fourth, renewable and efficiency-raising technologies are evolving extremely rapidly. Some key technical issues require analysis and Federal policy action immediately--such as the preparedness aspects of grid integration (pp. 226-228) and the encouragement of multifuel capability in cars (p. 242). Without proper handling of these issues, many of the potential preparedness benefits of spontaneous efficiency and renewables programs will not be realized. The few analytic groups that had begun to consider such questions, notably at the Solar Energy Research Institute, have been disbanded, and the private sector has no incentive to take their place.

More broadly, the patterns and processes of Federal thinking about energy need to be leavened by a greater awareness of the nature of vulnerability and how to combat it. The best Federal energy preparedness planning today appears to be in the Department of Defense--as exemplified by impressive retrofit and renewables programs at some military bases--but the details and rationale of this work are not well known to civilians, even in the Department of Energy. DOD proposed some years ago to have a liaison in the office of the Secretary of Energy to ensure that vulnerability got proper attention; but this was never done, and over the years, diverse DOE managers have continued, incrementally and unknowingly, to increase the vulnerability of America's energy system.

There is a similar opportunity to strengthen coordination between FEMA, DOE, and Interior to ensure that the concerns which are FEMA's statutory responsibility receive due weight in, and are not undercut by, other agencies' decisions taken on other grounds. It would also be worthwhile to improve liaison with those members of Congress who have shown particular expertise and interest in energy resilience (as in Senator Percy's study of a possible National Defense Alcohol Fuel Reserve). Currently, whether in the Executive or the Legislative branch, Federal programs and plans which affect energy vulnerability--in either direction--tend to be specialized, scattered, and uncoordinated. It is understandable that FEMA should be somewhat preoccupied by such complex and specific responsibilities such as nuclear evacuation plans and post-attack planning. But someone--if not FEMA, then some other expert agency--must begin to consider the much broader canvas of planning for resilience which this study describes*.

In summary: our consideration of energy preparedness, and our experience with hundreds of local and regional energy efforts around the country, leads us to conclude that the most fruitful roles for an agency like FEMA in promoting energy preparedness would be to raise the consciousness, expertise, and public accountability of those Federal agencies whose decisions are increasing energy vulnerability; to identify and coordinate Federal action on those detailed gaps in Federal planning which we have identified (such as grid integration); and to

*Indeed, we hope FEMA will apply to many other areas of national vulnerability the style of analysis we use here. The production and distribution of food is an obvious case: supply lines are currently so long that a truckers' strike or bad weather can put many retail food stores, especially in the East, on short rations in a matter of days. The reasons for this vulnerability are much the same (long supply lines, tight coupling, etc.) as those we identified for the energy system in Chapter 2.1, and potential remedies are also largely analogous. The promotion of greater self-reliance in food production as between regions of the country and between urban and rural areas could clearly make important contributions to national preparedness. In some instances, such as Alaska, such essential self-reliance used to exist but was systematically dismantled in the 1950s and 1960s in order to produce commercially rewarding dependence on a long supply line (in that case from Seattle). A few weeks' shipping strike in Seattle today would bring Alaska near to starvation; yet Alaska can easily be a net exporter of food, and holds many national records for vegetable growing. The Joint Committee on Defense Production [1977: 11:42-45] found that similar considerations apply to American industry, whose characteristics are tailor-made for easy disruption. The Committee found that correcting these defects, even at the margin and over many decades, could be very costly. But the cost of not doing so could be even higher--a rapid regression of tens or even hundreds of years in the evolution of the American economy, should it be suddenly and gravely disrupted. A third area where it would be important to apply a similar analysis is water policy--currently in the state of looming crisis that energy was in in the 1960s, and for strikingly similar reasons. Whether perceived or not, the true implications of these and other vulnerabilities will inexorably be borne in upon us by a surprise-full future. Energy policy is only the first of many choices between resilience and collapse.

use its influence and resources to spread information on the specifics of achieving greater energy resilience, especially by encouraging locally based "energy mobilizations" addressed to local security and economic concerns. Distributing instructions on how to use a truck as an improvised electric generator [e.g. DCPA 1977:App.G] is useful if all else has failed. But distributing instructions on how to make buildings and factories efficient, how to harness renewable sources in the service of energy preparedness, how to improvise efficiency and renewable technologies out of locally available materials, and how to integrate new energy devices in the way most supportive of preparedness goals would fill an information gap which no other actor is likely to fill--and be the best insurance against ever having to hook up that truck generator.

A useful first step would be for FEMA to serve as a visible focus for Federal efforts at energy preparedness, helping DOE to coordinate its efforts to ensure that day-to-day decisions serve to increase, not reduce, energy resilience. But to go further--to offer Americans the informational tools they need to turn from managing curtailments to preventing curtailments--would be a far greater step, and one better fulfilling FEMA's broader mission: to help build a nation in which emergencies needing management are unlikely to arise.

Today our nation uses an energy system so brittle that major energy emergencies are not only possible but expected. If FEMA harnesses the latent ingenuity and commitment of millions of citizens who are concerned about this vulnerability, and who wish--in both their own and the national interest--to build a more secure and stable energy future, the changes already underway in America's energy system can, we believe, be greatly smoothed and speeded. This will require sensitivity to local needs, and a philosophy of encouraging grass-roots initiatives rather than imposing requirements. But if it is done, the reward will be a sustainable foundation for national prosperity, an energy system that contributes to that prosperity rather than sapping it, and a tangible basis for regaining a sense of security in our lives and freedoms.

* * *

APPENDIX A: RISKS TO THE SOLVENCY OF ELECTRIC UTILITIES

[This Appendix is in the form of an unsolicited memorandum, sent by A.B. Lovins on 26 February 1981 to the Secretaries of the Treasury and Commerce, the Director of Management and Budget, other government officials, several members of Congress, members of the financial and academic communities concerned with utility issues, and utility executives and regulators. As of mid-May 1981, responses had been received--all favorable--only from the non-governmental recipients. A slightly edited version is to be published in The Energy Journal (International Association of Energy Economists) later in 1981. The memorandum, originally entitled "How To Keep Electric Utilities Solvent," follows in full:]

An urgent policy issue likely to confront you this year or next is how to keep one or more major U.S. investor-owned utilities [1] from becoming visibly bankrupt. The fiscal and psychological fallout could be severe, because vast amounts of utility debt and equity are built into the base of our nation's highly leveraged capital structure. If confidence in the worth of those assets were eroded by something worse than ConEd's dividend omission seven years ago, there could be disproportionate and unmanageable effects on banks, insurance companies, and pension funds. At least one regional Fed office is already worrying about how to bail out some local banks that are up to their necks in dubious utility paper.

During the past few years I have worked with many utility executives, bankers, and regulators to try to restore utilities to financial integrity through a better understanding of their predicament. From this perspective I am concerned that the reflex actions most likely to be proposed to you in a crisis are liable to make the utilities worse off and thus to increase financial risks to an even more intractable level.

The conventional wisdom of the industry and, until recently, of most financial analysts holds that the utilities would be healthy but for an unfavorable regulatory climate that gives them (belatedly) only half the rate relief they want. In this view, if the utilities were unregulated or at least more sympathetically regulated, they would be commercially viable enterprises. I believe this view is false for three reasons:

1. Utility cash-flow is inherently unstable--to the point that any utility, whether regulated badly, perfectly, or not at all, will go broke if it keeps building power stations.
2. Long-run price elasticity of revenue may be negative--in which case construction, by incurring higher marginal costs, would require higher revenues to maintain it but would produce lower revenues.
3. The utilities' financial problem is not merely fiscal but also fundamentally economic: all of their marginal output and much of their current output is simply uncompetitive in an end-users' market.

Let me now briefly argue for each of these propositions, leaving the details for cited references and, if you wish, for discussion.

1. Many public utilities have analogous problems. See e.g. Washington State Senate Energy & Utilities Committee, WPPSS Inquiry Report, 1981: the \$5.5 billion in bonds sold, part of the largest non-federal public borrowing program in the U.S., have already incurred carrying charges totalling >\$46 billion in current dollars; yet far more money is needed.

1. Utility cash-flow is inherently unstable [2].

Electric utilities are extraordinarily capital-intensive--about a hundred times as much as the traditional direct-fuel energy systems on which the American economy was built. Owing to the scale and complexity of the technologies, construction lead times for traditional major utility investments are irreducibly several times longer than the time constant for short-run price elasticity of demand. Accordingly, a utility that orders a power plant will inevitably overbuild. Higher marginal costs require higher prices to maintain financial health during construction. These higher prices dampen demand growth below the expected level; thus when the plant is commissioned, demand and hence revenues are inadequate to cover fixed charges. This shortfall induces still higher prices, dampening demand growth--or, in some cases, the level of demand--still further, thus increasing overcapacity and eroding cash-flow still more. If demand at the time of plant completion falls persistently short of expectations, cash-flow will progressively collapse.

So far into this "spiral of impossibility" are U.S. utilities that if every power-plant construction project in the country were cancelled now, and if we had for the rest of the century twice the rate of peak demand growth we had in 1979 (a "normal" year with 3.2% real GNP growth), then in 2000, we would still have nationally--ignoring significant regional differences--a prudent 15% reserve margin, just by working off the fat. (This does not count price-induced acceleration of improvements in electrical productivity, nor 200+ GWe of available cogeneration, nor other alternatives.) This overcapacity has built up through demand forecasts so exaggerated that during 1974-79, investor-owned utilities' forecasts of peak demand one year ahead averaged 2.6 times the actual growth. Had the utilities enjoyed perfect information about cash needs and price elasticity a decade ahead, they could in principle have avoided overshoot. But data and forecasting tools are grossly unequal to this task, and in practice, most utilities predicted demand based on current or rolled-in prices, very low price elasticity, and underestimated cash requirements.

Many second-order effects make the instability worse, including some acting through capital markets and accounting methods. Utilities' reliance on Allowance for Funds Used During Construction (a fictitious, non-cash income item now constituting about half their net income) makes cash-flow collapse faster if in fact the construction is not finished or if its output cannot be sold: the real cash position, not its AFUDC-booster facade, then becomes apparent. The possibility, based on several recent precedents, that state Commissions may exclude unneeded plant completions from rate base also heightens the risk of not being made whole.

Would commonly proposed measures to boost cash-flow correct its instability? No. For example, putting construction work in progress (CWIP) into the rate base gives price elasticity longer to work during construction --it approximates a sort of marginal-cost pricing up front--and thus increases the shortfall in revenue when the plant is completed. (An alert utility which anticipated this could of course cancel the construction, but then there'd be no CWIP to argue about.) Rate-based CWIP is economically dubious because it makes ratepayers finance compulsorily an investment which investors are unwilling to finance themselves. But besides evading the salutary discipline of the capital marketplace, it is not even in the utilities' long-term interest because it would ultimately only increase overcapacity.

2. This argument is expanded and documented in my March 1979 E.F. Hutton conference paper "Electric Utility Investments: Excelsior or Confetti?", reprinted Spring 1981 in J. Bus. Admin. 12(2) [Vancouver].

What about increased subsidies--faster depreciation, bigger investment tax credit, mandatory phantom taxes in flow-through states, etc.? These would further inflate the utilities' construction beyond their ability to amortize it from revenues, making them crash harder just a few years later. Indeed, present tax subsidies and rolled-in pricing can in significant part be blamed for having led the utilities down the path to ruin. Each of these terms reduces the marginal delivered price by about 1.5-2¢/kW-h. Thus, conservatively assuming unitary price elasticity, demand at the margin is being roughly doubled from an economically efficient level (clearing at the shadow price); or, to put it differently, utilities are led to overinvest in supply, as against increased energy productivity, by about twofold--a misallocation of over \$100 billion.

In short, a disparity of time constants between construction and price response makes cash-flow unstable--the classic control-theory instability of any system with long lags. Reconciling the two time constants can cure the instability, but subsidies make it worse. It is like having a furnace controlled by a thermostat at the end of a long corridor: the corridor will overheat before the thermostat can tell the furnace to shut off. Moving the thermostat up next to the furnace reduces the time-lag and can eliminate the overshoot. Turning up the thermostat or enlarging the furnace merely exacerbates it.

2. Higher prices may reduce long-run revenues.

Both recent observations of empirical marketplace behavior and detailed new engineering/economic studies of the scope for using electricity more efficiently (see #3 below) have led many analysts of energy demand to suspect that clearance of institutional barriers to efficient investment will elicit long-run price elasticities of demand for electricity of at least -1.0 and probably more: -1.5 is reasonable and even -2.0 is not impossible. If the absolute value of the elasticity exceeds one, then absent compensatory growth in population or income, price elasticity of revenue is negative. Higher prices would then lose the utility more on the number of kilowatt-hours it sold than it would make up by charging more for each kilowatt-hour. Nobody knows yet whether this is the case, but if it were, a rational utility seeking higher revenues should reduce its rates and its rate base.

When marginal costs started to exceed historic costs, around 1970, it took many utilities ten years to realize that building more plants is not in their economic interest: they never get their money back. It may now take some utilities another decade to realize that rate relief is not a panacea and may even dig them into a deeper hole.

3. Utilities' product is basically uncompetitive.

There is no demand for electricity per se. Raw kilowatt-hours are not a useful commodity. The real demand is for energy services: comfort, light, mobility, ability to smelt alumina or run sewing-machines. End-users desiring these services have a wide choice of how to provide them: raising their energy productivity, buying electricity, or buying some other form of energy. In a free market, end-users can be expected to choose the amount, type, and source of energy that will provide each desired service as lowest private internal cost. This will often mean buying less electricity--precisely what many consumers are starting to do.

Electricity is a special, high-quality, extremely expensive form of energy. Today's average delivered price, around 5¢/kW-h, is equivalent to buying the heat content of oil priced at \$80/bbl. A typical marginal

delivered price, 8¢/kW-h in 1980 \$, is equivalent on a heat basis to buying oil at \$130/bbl, four times today's OPEC oil price. Such expensive energy may be worthwhile for certain premium applications such as smelters, lights, motors, appliances, and subways. It is, however, fundamentally uneconomic for thermal applications, even if used in a very efficient heat pump. It also cannot compete in the road-vehicle market against really efficient fueled cars, especially series hybrids. These economic conclusions are robust and not vulnerable to technical change.

The end-use energy requirements of the U.S. economy are currently:

heat (mainly at low temperatures).....	58%
vehicular liquid fuels.....	34%
electricity-specific applications.....	8%
TOTAL DELIVERED ENERGY NEEDS..100%	

Only 8%, then, of all delivered energy requires and (at marginal price) can economically justify electricity; but 13% of all delivered energy is currently supplied in the form of electricity, and 16% would be if plants were not sitting idle. Thus the real electrical market is already filled up twice over by today's power stations. Two-fifths of all U.S. electricity sold is already being used uneconomically for low-temperature heating and cooling: space heating, water heating, and air conditioning. Still more could only be so used--like cutting butter with a chainsaw.

There is thus no marginal market for electricity in the United States, because the premium applications for this costly form of energy are already saturated. Arguing about which kind of power station to buy is somewhat like shopping for the best buy in brandy to burn in your car, or the best buy in Chippendales to burn in your stove. It does not matter whether one kind of proposed new power station will be able to provide cheaper kilowatt-hours than another kind, because no kind of new power station can come close to competing with the real competitors--the cheapest ways to provide the same energy services. Those real competitors, equally available to end-users, are such measures as weatherstripping, insulation, heat exchangers, window shades, and greenhouses. They can provide the user with heating or cooling not at the 8¢ it would cost with marginal electricity (3-4¢ with a good heat pump), but rather at about 0.4¢/kW-h. No thermal power station, new or old, can compete with that.

This finding has been confirmed in detail by Roger Sant in his study of "The Least-Cost Energy Strategy" [3]. He showed that at rolled-in 1978 prices, some 43% of the electricity sold in the U.S. was uncompetitive with efficiency improvements that would provide consumers with the same energy services at lower cost. What would happen, however, if we made this comparison at marginal delivered prices--as we should do to minimize social cost? My analysis, not to Sant's surprise, suggests that the electricity saving would then be so large that all of the thermally generated electricity in the country may become uncompetitive!

This is mainly because there is an enormous scope, just now starting to be appreciated, for raising the energy productivity of non-thermal uses of electricity through cost-effective technical measures. For example, lighting efficiency can typically be trebled, at a price under 0.5¢/kW-h, by task-lighting, daylighting, and efficient lights and fixtures. The practical efficiency of industrial electric motors can generally be doubled by proper sizing, coupling, and controls, at a cost often below 0.8¢/kW-h--a payback of 3-4 years. (Just this one saving would more than

3. Energy Productivity Center, Mellon Institute (Suite 1200, 1925 N. Lynn St., Arlington VA 22209; Harv. Bus. Rev. 6&ff, May-June 1980. My analysis is documented in Energy/War (ref. 6) at pr 47-53 and 96-100.

displace the entire U.S. nuclear power program.) Intelligent redesign costing 1.1¢/kW-h (6-year payback at 5¢/kW-h) can quadruple the average efficiency of household appliances with no loss of convenience. Other such examples abound. It is for this reason that Sant's latest analysis, constructing from many hundreds of sectors a "least-cost strategy" for providing energy services in the year 2000, finds it is seldom worthwhile even to finish building the power stations now under construction.

Further confirmation comes from an analysis commissioned by John Sawhill in 1979 from consultants directed by Henry Kelly at the Solar Energy Research Institute. They explored U.S. energy needs if real GNP were to increase by two-thirds during 1980-2000, assuming that energy investments were meanwhile based on least marginal cost to the consumer and were neutral as between increasing supply and increasing efficiency. The result was a total primary energy demand in 2000 reduced by at least a quarter below today's level, a total nonrenewable fuel requirement cut by nearly half, and a flat or declining total demand for electricity. Even the presently installed coal and hydro plants provided more electricity than careful analysis could find an economically rational use for. This implies, as Sant's most recent work has found explicitly, that total U.S. energy costs as a fraction of GNP could actually decline. The energy sector, far from driving inflation, would become a net exporter of capital to the rest of the economy. Increased energy productivity would become a principal engine of economic growth.

This is good news for the economy as a whole, but it is bad news for utilities, for it means that they have over \$100 billion worth of thermal plants which they may be unable to amortize. Utilities must now compete not only with efficiency improvements, but also with alternative generation options from which, under the Public Utility Regulatory Policies Act of 1978 (PURPA), they must buy back surplus power at their own "avoided cost"--in oil-burning New Hampshire, 7.7-8.2¢/kW-h. Entrepreneurs are therefore installing dispersed generation whose output is to be profitably sold to still other entrepreneurs who in turn profitably sell it back to utilities. What are these alternative options with which existing thermal plants must compete? A utility seeking more electricity can get it from these sources, in approximate order of increasing price:

- a. Eliminate pure waste of electricity, like lighting empty offices at headache level. A kilowatt-hour saved is a kilowatt-hour earned. It can be resold to some other customer without generating it anew.
- b. Displace with efficiency improvements, passive solar measures, and some cost-effective active solar measures the two-fifths of electricity now used for low-temperature heating and cooling. (That is why some Northwest private utilities now offer zero-interest insulation loans: the electricity saved is far cheaper than new generation.)
- c. Make the lights, motors, smelters, appliances, etc. cost-effectively efficient compared to building a new plant. (TVA has been developing a proposal to treat such efficiency improvements as equivalent to new generation, eligible for PURPA buyback in the form of a TVA voucher applicable to the purchase price of the equipment.)

Just these first three measures will, I believe, approximately quadruple U.S. electrical use efficiency [4], at a cost generally below present

4. The main terms are (b), saving two-fifths of total electricity, and Industrial motor retrofits, saving over a quarter of the rest. The most detailed analysis of measures (a)-(d), done by my colleague David Olivier for the U.K. Atomic Energy Authority, shows a nearly sevenfold improvement in British electrical efficiency at well below the cost of (e).

rolled-in prices. The resulting demand could be met with no thermal plants, old or new, but only present hydro, small-scale hydro, and a modest amount of windpower. But if still more electricity were desired, the next higher points up the electricity supply curve would include:

d. Industrial cogeneration, combined-heat-and-power stations, low-temperature heat engines operated by industrial waste heat or solar ponds, filling empty turbine bays in existing large dams, modern wind machines or microhydro in good sites, or possibly new developments in photovoltaics (especially using cheap optical concentrators and waste-heat recovery for an economic credit [5]).

It is only after all these options had been exhausted that one would even consider

e. Building a new central power station--

because that is the costliest and slowest known way to get more electricity (or to save oil).[6]

Given this array of options, what follows from PURPA's creation of a competitive market in generation? There is currently a strong economic incentive to install your own generating capacity--in your factory, in your backyard, or (as cheap solar cells arrive in the next few years) on your roof. Whatever power you sell, the utility must pay you "avoided cost" for it. But your power is not only cheaper than the utility's marginal cost; it may well undercut the rolled-in price too. Your competition reduces the utility's revenues while increasing its overcapacity and hence its burden of fixed charges per kilowatt-hour sold. The utility must therefore raise its price. But that increases your incentive to generate and resell more. Where this positive feedback loop ends, I suspect, is in the economic and technical obsolescence, over the next ten to twenty years, of \$100-200 billion net worth of thermal generating plants. Repealing PURPA would not prevent, but only slightly postpone, this outcome--the inevitable fate of a capital stock that is fundamentally uncompetitive even in marginal operating costs with existing alternatives widely available to end-users.

Is this really true, not only of the admittedly expensive new plants--option (e) above--but also of existing thermal plants whose capital cost is already sunk? The only marginal internal cost of operating them is their cost of fuel, plus operation and maintenance for the plant and perhaps for its associated marginal grid. For a nuclear plant, depending on age, that cost (neglecting the present value of waste management and decommissioning) can be as low as about 1-2¢/kW-h. But even that is more than the cost of efficiency improvements--like the 0.4¢/kW-h weatherization and the 0.6-0.8¢/kW-h industrial motor retrofits--which are collectively sufficient to displace all existing nuclear, oil, and gas capacity. Thus if one had just built a new nuclear power plant, one would save the country money by writing it off and never operating it! Under U.S. tax laws, the additional saving from not having to pay its stream of

5. DOE now expects central-station photovoltaics--far from the most cost-effective application--to compete on U.S. grids in 1986. Many dispersed uses, especially with cogeneration, are worthwhile already or will be within a year or two. This assumes only existing technology; but second-generation cells which promise to be far cheaper are likely to be here in the next few years before we know what to do with them.

6. My 1 January 1981 memo to David Stockman describes how two measures with payback times of a few years can eliminate U.S. oil imports by about 1990. See also Energy/War: Breaking the Nuclear Link (Friends of the Earth, 124 Spear St., San Francisco CA 94105), 1980, pp. 91-98.

future subsidies and profits would probably suffice to recoup its sunk capital costs too [7].

With competition in their territories raising their own overcapacity, many utilities plan to sell their surplus output to someone else--traditionally the utility next door. Today the assumed long-term market is in particular regions, assumed to represent "black holes"--infinite inelastic markets for electricity, such as New England, New York, Florida, Mississippi, Arizona, and California. (TVA even has ambitions to wheel power to Arizona!) Unfortunately, a great many utilities are hoping to sell gigantic surpluses to these same black holes simultaneously. It won't work. More utilities--including many in Canada--will be seeking to sell more electricity to an ever smaller U.S. market. There is no geographic escape from the uncompetitiveness of the utilities' product.

Nor is there an escape through higher prices, in whatever guise. Roger Sant was recently discussing his findings with some utility executives. They nonetheless continued to call for rate relief--until John Bryson, President of the California PUC, said, "Roger's just been telling you that at the 1978 prices, 43% of your product was uncompetitive. Now you want higher prices so that maybe 60% or 80% will be uncompetitive?" Higher prices, like higher subsidies, are worse than a merely cosmetic approach to the utilities' disease; they actually reinforce it.

Powerful market forces are converging on the utilities: high interest rates, falling ratios (current, coverage, and market/book), increasing dependence on "funny money" (AFUDC) and other creative bookkeeping, stagnant demand, real cost escalation, greater consumer opposition to rate hikes, heavy short-term borrowing to pay dividends, shareholder efforts to prevent further dilution of equity (thus forcing even higher debt/equity ratios), and many more. These signals are not fortuitous artifacts. They offer unmistakable evidence that the utilities' financial problems are of a fundamental nature--both fiscal and economic. A utility can go broke without suffering a catastrophic GPU-style loss-of-cash-flow accident, simply because its business takes too much cash, pays it back too slowly, is unexpectedly price-elastic, and cannot compete.

Even the most gifted managers would be hard pressed to sustain such an unpromising venture; but the utility sector is oversupplied with mediocre managers, often with grievously little prospect of attracting better. The hottest management seat in industry today is finding few inspired takers. However this long-standing problem of management quality is to be resolved, the market is clearly signalling that utilities are no longer a sound investment. How, then can the utility sector be smoothly recycled into a form whose product the market is willing to buy, and how can we meanwhile avoid serious dislocations in our financial system?

What is to be done?

I have summarized elsewhere [2,8] a possible framework for remedy which appears to merit prompt attention and refinement. It includes:

1. Utilities should be considered in the business of supplying, not kilowatt-hours per se, but rather energy services or the financial means of providing them (a position already adopted by some well-managed private utilities and by the American Public Power Association).

7. For details, see Energy/War, op. cit. [6], pp. 48-49.

8. California PUC (San Francisco), Energy Efficiency and the Utilities: New Directions, 1980, pp 168-78 (concluding keynote); see also 72, 139-42, 151-2, 165, and many other statements by industry leaders.

2. State utility Commissions should, like California's and Idaho's, permit new construction (or, generally, continuation of existing major construction) only if that marginal investment is shown to be the cheapest way to provide the incremental energy services for which the incremental electricity would be used. Otherwise, utilities should loan out their money on mutually advantageous terms so consumers of all classes can do the cheaper things first. (To keep this "investment balancing test" honest, a utility which passes it and builds the plant should not be allowed to rate-base more than the real plant cost it assumed when comparing the proposed plant with other options.)

3. The loans should be made at the utility's post-subsidy cost of money (in practice, near embedded cost, for reasons explained below). Borrowers would then pay back the loans through their bills only as fast as the energy saving saves them money--the TVA "graduated-payback" system. Borrowers would thus need no capital, and all options would enjoy equal access to capital, encouraging fair competition.

4. The loans--which I call "capital transfers"--should be made from a revolving fund "below the line", i.e. neither rate-based nor expensed, though transaction costs could be expensed. (Two-fifths of U.S. generating capacity belongs to utilities already giving or about to give analogous loans: generally with rate-basing, fast payback, and subsidized interest--a less efficient scheme than that proposed here.)

5. Rate reform should as nearly as possible ensure that incremental consumption attracts true incremental cost.

6. Cooperating utilities' deferred taxes under accelerated depreciation--an overhang nationally totalling some \$13 billion (mixed current \$) which falls due when a utility stops growing--should probably be forgiven. The Treasury was not going to get most of it anyway, since it was being shoved off into the never-never and paid in vastly inflated dollars. The forgiveness should preferably be part of a broader Batinovich-style plan [2,9] to desubsidize the utilities systematically by abolishing their federal income taxes. (Most of them currently pay negative taxes, at least on marginal investments. The tax timing inefficiently encourages premature construction and premature retirement; the subsidies are unnecessary and inefficient for a regulated monopoly required to meet demand anyhow; and any revenue gain would be more simply obtained by a direct electricity excise.)

This package of measures would have the following consequences:

a. Consumers, regardless of class or income, can make any fuel-saving investments which are cheaper than marginal utility investments, but without needing the capital up front.

b. Utilities can participate--at arm's length--in the highest-return investments in the entire economy. (They would not own, lease, install, control, or specify the investments; measures are available to protect consumers from supplier fraud without projecting utilities into a business they are not good at or risking an appearance or fact of anti-competitive activity.) The new marginal investments would yield about ten times as much energy per dollar as those they replace.

c. Instead of tying up dollars in a power plant that pays back in 30-40 years (if ever), utilities can turn dollars over every few years, about ten times as fast. This greatly increased velocity of cash-flow

9. C. Davis provides an excellent analysis of utility subsidies and why to remove them: 4 Harv. Envir. L. Rev. 311-358 (1980).

will enable many utilities to finance a larger energy program than they had before, but without needing to go to the market for new debt or equity capital: they can merely bootstrap their retained earnings (totalling some \$11 billion a year, of which perhaps half is real money) because the revolving fund revolves so quickly. Because the capital is largely or wholly internal--embedded capital already earning a return--the utility can loan at close to its embedded cost of money. It then takes the cash-flow benefit of avoiding the high marginal cost of new money from outside. (There are also obviously some national macroeconomic benefits for interest rates, employment, etc.)

d. Utilities can have, at the margin, a short-lead-time, fast-payback business. Its short time constants remove the instability in their cash-flow. They are no longer at risk of going broke by building more plants than they can pay for. New construction, having failed the investment-balancing test, is no longer hemorrhaging cash.

e. All marginal investment opportunities to provide energy services are now being symmetrically compared, not with old cheap natural gas, but with the marginal cost represented by the proposed new plant. Most of the capital going into the U.S. energy system is therefore being allocated as if energy were priced at the margin, whether it is or not. We have thus largely done an end-run around the awkward problem of finding energy prices that are both equitable and efficient.

f. For the next fifty years or so, as they turn into a distribution service like the telephone company, utilities have something useful to do which they can do well and feel good about. They are using their financial talents and existing billing relationships to minimize transaction costs. Their goal is a socially efficient allocation of capital to meet consumers' energy service needs at least cost.

g. Unlike plans which rate-base conservation loans, this scheme leaves the incentive to invest efficiently in the hands of the party (the householder, factory-owner, etc.) who is making the investment. Further, treating the loan below the line protects the utility if price elasticity of revenue turns out to be negative. The utility's passed-through cost of money is a wash; the utility's return is unchanged; and the utility's cash-flow benefits are enormous.

h. Unlike plans which offer low- or zero-interest loans, this scheme permits and indeed requires investment in alternatives up to the marginal cost of conventional supply. No complex "no-losers" test is required, since nonparticipants benefit instead of being penalized.

i. Though this scheme could be facilitated by federal action, especially in tax reform, it can probably be done entirely at a state level, often without new legislation. Only existing institutions, modestly adapted, would be needed.

The foregoing proposals address both the fiscal problems of the utilities --by stabilizing cash-flow and prices--and their economic problems--by redirecting their marginal investments into competitive channels. There will undoubtedly turn out to be special cases requiring special treatment. (For example, some utilities have no retained earnings with which to capitalize a revolving fund. Possible alternative sources of initial capitalization include public bond issues and a couple of years' temporarily excess tailblock revenues in the course of flattening or inverting an existing declining-block rate structure.) But the general principles presented here appear to be consistent with sound market theory logically applied to utilities' pressing financial problems. That is why many utilities are expressing great interest in exploring and refining them.

I therefore hope you will be duly skeptical about doctrinaire assumptions that power-plant construction is vital to the national welfare; that utility rate relief is essential to their financial integrity; and that lame-duck utilities are so important to preserve in unaltered form that they must be resuscitated by heroic measures, notably subsidies of the kind urged in the transition-team Halbouty Report from the President's Energy Advisory Task Force. There is compelling evidence, on the contrary [10], that power-plant construction is an egregious misuse of scarce national resources and will retard oil displacement by diverting investment from measures that would save more oil faster and cheaper [6]; that Commissions reluctant to grant rate relief uncritically are doing their best to save utilities from their own folly; and that more subsidies are the surest way to ensure the bankruptcy of the utility sector on a scale beyond the ability even of the Treasury to bail it out.

Should you wish to pursue these concepts further, I should be glad to meet with you or your advisors on one of my forthcoming visits to Washington. Meanwhile, let me suggest that there is a case for setting up without delay a small, high-powered task force of analysts who have already devoted a great deal of thought to these problems. I should be glad to help you identify key people, mainly in the financial community, whose insights could be of lasting national service. If your Department waits until a Chrysler-like situation has actually developed, flexibility of action will already be severely constrained and a large measure of the public confidence which one had sought to preserve will already stand in jeopardy. It is vital to use this short breathing-space to develop in advance some prudent contingency plans. Only thus can you have at hand, when a politically visible crisis does loom, the background analyses you will need to forestall hasty and ill-considered proposals that do not grasp the full depth of the utilities' plight.

10. Among the most cogent demonstrations that utilities' financial risk can be greatly reduced and their cash-flow markedly improved by abandoning partly built power stations in favor of efficiency/renewables investments is E. Kahn et al.'s "Commercialization of Solar Energy by Regulated Utilities: Economic and Financial Risk Analysis," LBL-11398, October 1980, Lawrence Berkeley Laboratory (Berkeley CA 94720): see especially Figs. 6 and 8.

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Nuclear weapons and power-reactor plutonium

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With modest design sophistication, high-burn-up plutonium from power reactors can produce powerful and predictable nuclear explosions. There is no way to 'denature' plutonium. Power reactors are not implausible but rather attractive as military production reactors. Current promotion of quasi-civilian nuclear facilities rests, dangerously, on contrary assumptions.

NUCLEAR policy, especially in Europe, has often been justified by the belief¹⁻¹⁰ that for making nuclear bombs, 'reactor-grade' plutonium produced by the normal operation of uranium-fuelled power reactors is necessarily much inferior to specially made 'weapons-grade' Pu: so inferior in explosive power or predictability that its potential use by amateurs is not a serious problem and that governments would instead make the higher-performance weapons-grade Pu in special production reactors.

Although that belief is false it was vigorously asserted during 1978-79 by responsible Ministers or by Prime Ministers in at least three high-technology nations. This was apparently because some of their nuclear experts did not know differently, and rejected contrary official US statements as being exaggerated or even politically motivated; or because those experts who did know were not asked; or because correct technical advice was lost, oversimplified, or garbled in transmission through advisors who did not understand the physics. Here I attempt to clarify the properties and performance of various grades of Pu, outlining the physical logic explicitly enough to ensure understanding although discreetly so as not to help the malicious: certain details and technical references have, therefore, been omitted and some calculations treated in conclusory fashion.

The possible military utility of power-reactor Pu has caused widespread professional confusion since 1946. Although some leading scientists appreciated even then^{1,11} that it was useable in bombs or might become so, the contrary assumption (admittedly hedged) was made in the Acheson-Lilienthal report^{12,13}. This recommended that certain nuclear activities could be classified as 'safe' because the Pu they produced could not be converted without timely warning into weapons-useable form, and that these activities could thus be carried out by nations if under strict and enforceable international controls. With the radical 1953 Atoms for Peace initiative, the report's finding that international inspections and treaties could not stop proliferation was forgotten, and US nuclear knowledge and materials were distributed worldwide with increasing enthusiasm and decreasing care¹⁴—apparently on the assumption that power-reactor Pu was, or could be made, unsuitable for use in bombs ('denatured'), despite the US Atomic Energy Commission's refutation of this notion¹⁵ in 1952. With this in many signatories' minds, the Non-Proliferation Treaty (NPT) was negotiated in 1967: an important fact to recall when construing the NPT today, even though its text and the International Atomic Energy Agency (IAEA) do not distinguish in quality between Pu made in power or in military production reactors.

Beginning publicly in the early 1970s in the US (earlier in the Soviet Union and France¹⁶), the assumption that power-reactor Pu was unsuitable for bombs was questioned with increasing force¹⁷⁻¹⁹. By 1974, authoritative reports¹⁹⁻²¹ had concluded that

reactor-grade Pu could be used even by amateurs to make effective fission bombs, albeit of somewhat reduced and uncertain yield²¹⁻²⁵. Further analyses during 1976-77, mainly at the US weapons laboratories, revealed a still wider spectrum of technical possibilities, and in 1977 the US announced that it had successfully tested a bomb made from reactor-grade Pu^{26,27}. Yet the earlier finding that this material, though useable, was inferior if used in relatively crude bomb designs was widely and wrongly supposed to apply to all designs. In particular, reactor-grade Pu was alleged to be inherently:

- far more hazardous than weapons-grade Pu to people dealing with it; or
- far more likely to cause unintentional explosions; or
- incapable of exploding violently enough to do much damage, or, at worst, to accomplish most military aims; or
- too unpredictable in explosive yield to be acceptable to its users.

Each of these assumptions contains, in certain circumstances, some truth; but each is generally, or can be by plausible counter-measures be rendered, false. Their implication that reactor-grade Pu is not very dangerous, or unlikely to be attractive to governments, is wishful thinking, and causes the proliferation risks of 'civil' nuclear activities to be gravely underestimated.

In recent years, advocates of commercial Pu use, in referring to the bomb-making that might also result, have had to retreat "from the original concept of denaturing to the notion of making do with less than optimal material"²⁸; yet the earlier myth lingeringly distorts policy²⁸. To decide responsibly about nuclear power and nuclear fuel reprocessing, we must know exactly what "less than optimal" means, and hence must cautiously review published physical principles. The only thing more dangerous than discussing this subject is not discussing it; the lesson of Atoms for Peace may yet be that with Pu, we must get our assessments right the first time.

Plutonium production

All nuclear reactors fuelled with uranium²⁹ (notably the 0.7%-naturally-abundant species ²³⁵U) produce ²³⁹Pu by neutron absorption in fertile ²³⁸U. Some of the ²³⁹Pu formed is fissioned; an increasing fraction absorbs successively more neutrons to form higher Pu isotopes, chiefly ²⁴⁰Pu, ²⁴¹Pu, and transplutonic elements³⁰; and some of the resulting ²³⁹⁻²⁴²Pu (plus traces of ²³⁸Pu and related species) survives until the fuel is discharged. Depending^{19,24,25} on the type and detailed design of reactor, the composition of initial fuel, and the manner of operation, especially the burn-up (extent of exposure of the fuel to neutrons), the net Pu production of a 1-GWe power reactor is typically several hundred kg yr⁻¹, for example ~210-240 kg yr⁻¹ for a light-water reactor (LWR), the dominant commercial type

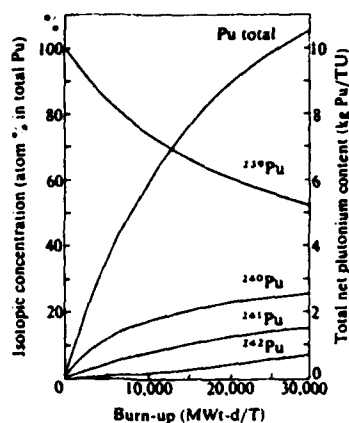


Fig. 1 Typical total amount and isotopic composition of plutonium in discharged fuel as a function of burn-up in a light-water reactor.³² The exact values depend in detail on reactor design and operation and on initial fuel composition. Higher isotopes of plutonium and transplutoniums become more abundant in repeatedly recycled fuel.

For a given reactor, the isotopic composition of the discharged Pu depends predictably on burn-up. If each metric ton of uranium (TU) yields only a few gigawatt-days' thermal energy (GWt-d), neutron capture is so limited that nearly pure ²³⁹Pu—'weapons-grade' Pu—is produced. It contains no more than 7% ²⁴⁰Pu or 8% ²⁴¹Pu, typically³¹ around 6%; perhaps 0.5% ²⁴²Pu; negligible ²⁴³Pu and ²⁴⁴Pu.

Higher burn-up, whether through leaving the fuel in the reactor longer or exposing it to a more intense neutron flux, produces a larger proportion of the higher Pu isotopes (Fig. 1). Low-enriched uranium fuel (the usual kind) left for the full 3–4 yr in a reliably operating LWR is usually designed for a nominal burn-up of 27–33 GWt-d/T. The latter corresponds³¹ to discharge Pu containing ~58% ²³⁹Pu and 11% ²⁴¹Pu (both fissile) plus 25% ²⁴⁰Pu, 4% ²⁴²Pu, and 2% ²³⁸Pu. This composition is broadly similar for other thermal or fast reactor types, except for graphite-moderated reactors³⁴ (²⁴⁰–²⁴²Pu ~ 20%) and fast breeder radial blankets³⁰ (~ 4%). In some circumstances the ²⁴⁰–²⁴²Pu fraction can rise from a nominal ~29% to as much as 49% (34% ²⁴⁰Pu, 15% ²⁴²Pu)³³ in equilibrium LWR Pu recycle fuel; this is unusually high and approximates a practical limit.

Power reactors also can, and often do, discharge fuel short of its full design burn-up. Mature US LWR cores routinely attain well below design burn-up³⁵. Real or simulated malfunctions, such as leaky fuel cladding, may lead the operator to discharge fuel at very low burn-up¹. Alternatively, manipulation of fuel rods can produce a core with high average burn-up but containing some rods of much lower burn-up. 'On-load-refuelling' reactors such as Magnox and CANDU are suitable for clandestine introduction, brief exposure, and removal of small but adequate amounts of fertile material in a few fuel channels. Such methods are not necessarily easy to detect even if an inspector were continuously present, and would probably not be detected at all by present international safeguards³⁶.

Because burn-up, and hence isotopic composition of discharged Pu, can vary enormously between and within reactors and with time, 'reactor-grade Pu' is not a well-defined term. Weapons-grade Pu, which is fairly well-defined (supra), can be readily produced in any power reactor without necessarily and significantly decreasing efficiency, increasing costs, or being detected. But though that option is always open, we assume here that it is not—that power reactors will be used to produce only high-burn-up Pu. We also assume that 'reactor-grade Pu' implies a ²⁴⁰–²⁴²Pu content of ~30%; higher, even arbitrarily higher, even-isotope content will not affect the argument, while a lower content would strengthen it. On these conservative assumptions, the Pu discharged from power reactors will be shown to have major military potential.

Plutonium properties

Relevant nuclear properties of the common Pu isotopes are summarised in Table 1. The values given for m_c are not the quantities needed to make a bomb, as neutron reflection and implosion can reduce critical mass by a large factor. This factor has been officially stated to be ~5, consistent with the US³⁰ and IAEA requirement of strict physical security measures for quantities of Pu ≥ 2 kg (independent of isotopic composition). Published data suggest, however, that with sophisticated design the factor may be >5. For example, in its densest (α -phase) allotropic form, ²³⁹Pu at normal density in a thick Be reflector has a reported critical mass as small as $m_c/4$, and large reflector savings are also obtainable with nonmoderating (and partly fast-fissionable) reflectors such as ²³⁸U. Further, if the core and reflector are equally compressible and if the ratio of reflector thickness to core radius remains constant during compression, critical mass varies as the inverse square of core density. Densities 'several times' normal are said to be attained in military

Table 1 Some properties of plutonium^{31,34,37,38}

Isotope	Decay properties		Specific activity (Ci g ⁻¹)	Heat (W kg ⁻¹)	Fast fission			Spontaneous fission	
	Half life (yr)	Main emission (MeV)			m_c^* (kg)	$\bar{\nu}^\dagger$	σ_f^\ddagger (barn)	Rate (n g ⁻¹ s ⁻¹)	$\bar{\nu}_{SF}^\S$
²³⁸ Pu	86.4	5.5 α	17.4	567	9	~3 ²	2.5 ¹	2,600	2.3
²³⁹ Pu	24,390	5.2 α	0.061	1.9	10	3.1	1.9	0.03	2.9
²⁴⁰ Pu	6,600	5.2 α	0.23	7.0	40	3.4	1.3	1,020	2.2
²⁴¹ Pu	13.2	0.021 β	112	4.5	12	3.2	1.8	—	—
²⁴² Pu	387,000	4.9 α	0.0038	0.1	90 [*]	3.3	1.2	1,670	2.3
²⁴¹ Am*	433	5.5 α	3.43	106	114 ^{**}	—	—	0.623	3.1

* Approximate bare-sphere prompt-critical mass at normal density; Pu is α -phase ($\rho = 19.8 \text{ g cm}^{-3}$). For comparison, m_c for 93.5% ²³⁵U ($\rho = 18.8 \text{ g cm}^{-3}$) is 49 kg ²³⁵U.

[†] Approximate gross neutron yield per fast fission (Argonne 16-group).

[‡] Approximate fast-fission cross-section (Argonne 16-group). (The capture-to-fission ratios are also important, and tend to be high for even Pu isotopes.)

[§] Approximate neutron yield per spontaneous fission.

^{||} Values cited by De Volpi³⁷, who gives the ²³⁸Pu m_c as 7 kg (unpublished); the best value calculated for α -phase, however, is the $m_c \sim 9.2$ kg shown here (R. W. Selden, personal communication).

^{*} Best Livermore estimate from the range 75–100 kg (R. W. Selden, personal communication). De Volpi³⁷ assumes ~95 kg (or 118 kg in Appendix H), but used ≥ 156 kg in earlier publications^{45,46}. Calculated m_c is probably not finite for ²⁴²Pu¹⁰B₂, owing to threshold effects, but is ~350 kg for ²⁴⁰Pu¹⁰B₂ at $\rho = 11.5 \text{ g cm}^{-3}$ (R. W. Selden, personal communication).

^{*} Daughter of ²⁴¹Pu, important (like the trace isotope ²³⁶Pu) mainly for its γ emissions.

^{**} Approximate estimate by Clayton¹⁸ for $\rho = 11.7 \text{ g cm}^{-3}$, implying reactivity comparable with ²⁴⁰Pu.

bombs⁴⁰, and by means described in the open literature a slightly subcritical mass of α -phase ^{239}Pu in a U reflector can be compressed to 1.85 times its initial density, corresponding to a reactivity increase of ~ 3.4 times. The same method can yield even higher compressions. Although high compression is inconsistent with simultaneous high reflection, it may be possible to achieve significant supercriticality with initial ^{239}Pu masses under 2 kg. Regardless of the exact figure, the IAEA's 8-kg 'significant quantity' design basis for detecting diversions¹⁶ seems far too high.

Of the Pu isotopes in Table 1, only ^{239}Pu and ^{241}Pu are fissile, that is, fissionable by thermal (slow) neutrons. All Pu isotopes, however, are fissionable by the fast neutrons in a bomb: indeed, at energies > 1 MeV (69% of fission neutrons) the fission cross-section of ^{240}Pu is less than that of ^{239}Pu by a margin of less than 20%, so the amount of ^{239}Pu required to form a normal-density critical mass is remarkably insensitive to ^{240}Pu content (Table 2). Published neutron transport calculations confirm that the even isotopes produce only minor changes in reactivity, neutron spectrum, and mean prompt-neutron lifetime. So reactive is ^{240}Pu that changing the ^{240}Pu content from 6 to 30% increases m_c only from ~ 11 to ~ 13 kg¹¹. No known fast-neutron absorber can make Pu of any practical composition incapable of forming a prompt-critical mass^{11,42}; calculations⁴² suggest that substituting the best fast-neutron absorber known, ^{10}B , for oxygen in reactor-grade crystal-density PuO_2 ($m_c \sim 35$ kg) would increase m_c only to ~ 70 kg.

Fast-fission properties of Pu, then, are only slightly affected by ordinary changes in isotopic composition. The neutron background is, however, modestly affected. Spontaneous-fission neutrons (Table 1) provide typically¹⁴ of the order of $100 \text{ n g}^{-1} \text{ s}^{-1}$ in weapons-grade Pu, about 500 in reactor-grade Pu. A further contribution (at lower neutron energies) comes from (α, n) reactions with light-element impurities. In Pu metal this is not an important neutron source¹⁴, but it can more than double the neutron background in PuO_2 , as 1 Ci of α -emitter bombarding oxygen produces of the order of $5,000 \text{ n s}^{-1}$.

Neutron background from all sources is significant for weapons physics (infra) and makes reactor-grade Pu give somewhat higher radiation doses than weapons-grade Pu. For long-term commercial handling within the normal canons of health physics, shielding would be required. For clandestine weapons manufacture it would not, because the published total dose rates (mainly γ and X rays) are relatively modest—of the order of rem h^{-1} at the surface of a 1-kg fresh recycled PuO_2 sphere, $< 1 \text{ mrem h}^{-1}$ at 1 m. Even under extreme assumptions (18% ^{238}Pu , 30% ^{240}Pu , 10-kg PuO_2 sphere with subcritical multiplication included), neutron dose rates (60 mrem h^{-1} at 1 m) do not provide an effective deterrent⁴⁴. It is obviously not correct that 'slight mistakes in the knowledge of exact [isotopic] composition . . . may well pose extreme radiological hazards'⁴⁴, given normal precautions against inadvertent criticality.

The specific activity of reactor-grade Pu is typically⁴² $\sim 10 \text{ Ci g}^{-1}$ as against 3 Ci g^{-1} for weapons grade Pu, the neutron background (for metal) and the inhalation toxicity ~ 5 times higher, and the heat production $\sim 10 \text{ W kg}^{-1}$ (about the same as for 1-yr-old spent LWR fuel) as against 3 W kg^{-1} . Only a difference of orders of magnitude in these quantities—the extent by which they all exceed the corresponding values for ^{235}U —would reflect differences in ease of handling that would be important in designing new bomb-making facilities⁴².

Thermal denaturing^{44,46} of reactor-grade Pu was recently proposed by A. K. Williams *et al.* (unpublished Allied-General Nuclear Services) and A. De Volpi¹⁷. The ^{238}Pu content would be increased from its normal 1–2% (nearly 5% in some recycle Pu^{11}) to 10–15%, perhaps nearly 20%, chiefly by recycling ^{23}Np itself a bomb material with $m_c \sim 75\text{--}105$ kg) with ^{232}Th rather than ^{235}U diluent⁴⁴. The ^{238}Pu would increase heat production to 6–9 times normal. Some calculations⁴⁴ based on cores of high mass and high volume to surface ratio, in direct contact with non-thermally stable explosives, suggest serious

Table 2 Critical mass of plutonium spheres in a $\sim 10\text{-cm}$ natural uranium reflector as a function of plutonium isotopic composition^{41*}

$^{240}\text{Pu}/^{242}\text{Pu}$ (atom %)	^{239}Pu in critical mass (kg)	Total Pu in critical mass (kg)
0	4.4	4.4
10	4.5	5.0
20	4.5	5.6
30	4.6	6.7
40	4.7	7.8
50	4.8	9.6

* Assuming $^{240}\text{Pu}/^{242}\text{Pu}$ ratio similar to that shown in Fig. 1

design problems. But realistic choices of geometry and materials can readily overcome these problems. Cooling does not even become an interesting design problem until the ^{238}Pu content approaches that of a thermoelectric heat source, and a much lower content, well over 20%, does not provide an effective deterrent even to most amateurs, though it would make safe and economic fuel-cycle operations hard to envisage⁴⁷. Only in quite incompetent hands could the extra heat pose a danger of unplanned detonation.

A second 'denaturing' proposal by De Volpi¹⁷ would combine ^{238}Pu and ^{240}Pu with extra ^{242}Pu , which is a diluent in fast spectra and something of a neutron poison in thermal spectra⁴⁸. Pathologically high ^{242}Pu content would increase m_c , though not by the ~ 30 times claimed by Olds⁴⁵ (compare Table 1); as all Pu isotopes have 'reasonably small critical masses, this concept [of denaturing by dilution] is not applicable to plutonium'⁴⁴. De Volpi states⁴⁶ that fuels made mostly of ^{242}Pu and with a fissile fraction as low as 18% are useable even in present fast reactors, but he does not analyse performance or economics, which apparently offer serious difficulties⁴⁴, and his analysis of weapons physics seems deeply flawed.

Synergisms are negligible, so the effect of each even Pu isotope can be dealt with separately: thermal 'denaturing' with ^{238}Pu above and neutronic 'denaturing' with all three isotopes below. Practicable dilution with ^{242}Pu cannot alter design constraints enough to affect the conclusions below.

Finally, nonmetallic forms of Pu must be considered. Reactor-grade Pu can be used directly in bombs without reduction to metal (though metal generally gives better performance). The oxygen in PuO_2 dilutes the Pu and lengthens the 'generation time' between fissions, reducing the yield, but it also slightly compensates by moderating the neutrons to lower energies where the fission cross-sections are higher. The dilution effect predominates and roughly doubles⁴² the δ -phase metallic m_c . It also alters other design parameters. Nonetheless, the oxygen is not a neutron poison and does not prevent attainment of 'large reactivity coefficients and short neutron life times'¹⁸ even in the much less reactive $^{235}\text{UO}_2$. Indeed, the low initial density ($\rho \sim 2.3 \text{ g cm}^{-3}$ uncompacted, 4.5 g cm^{-3} moderately compacted) of PuO_2 powder relative to its sintered (≈ 11.2) or crystal (11.5) density, and its relative compressibility at crystal density, permit crude designs with a generous safety margin of initial subcriticality to achieve high supercriticality after implosion. It is, therefore, not surprising that PuO_2 has been uniformly agreed to be directly useable in formidable explosives^{16,19,42,43,44}. A bomb made directly even from fresh LMFB mixed-oxide fuel (15–25% Pu) is theoretically possible⁴⁹, though unwieldy.

Weapons physics and reactor-grade plutonium

A nuclear explosion results from a divergent chain reaction in a prompt-supercritical mass, that is, one which can support a chain reaction by virtue only of the prompt neutrons released immediately by fission. The fission neutrons in a bomb are fast, with energies in the megavolt range and velocities of the order of $1.2 \times 10^8 \text{ cm s}^{-1}$. The fissionable material must be of sufficient

size and density that a neutron born within it is likely to cause a further fission within it. The critical masses discussed above imply that the mean distance between fissions is of the order of centimetres, hence that the mean time between fissions is of the order of 10^{-14} s. Roughly 40–50 generations of fissions are required to build up a fast chain reaction to an explosive level¹¹: $e^{40} = 2.4 \times 10^{17}$ fissions would release 1.6×10^4 kcal, equal to the nominal energy release from ~1.6 kg of high explosive and thus approaching the energy density needed to disassemble rapidly a Pu core of nominal size. Only the last few generations in this exponential process provide appreciable energy yield. That energy builds up, in a few hundredths of a microsecond, temperatures of several hundred million °C and pressures of the order of 10^4 bar, causing the core to expand with a velocity of the order of 10^4 cm s⁻¹. Expansion from the initial radius by a factor roughly equal to the sixth root of the number of critical masses present, that is, by ~1 cm, makes the mass subcritical and quenches the chain reaction. Once the explosion begins, then, only a few more generations of fission, producing most of the yield, are possible.

The designer seeks to assemble as supercritical a mass as possible (by 'inserting reactivity') as quickly as possible, and to inject neutrons to initiate the chain reaction at the optimal moment during that assembly—before the instant of maximum supercriticality, so that the bomb's tendency to fly apart is partly countered by the continuing forces of convergent assembly. The yield of the nuclear explosion depends strongly on the degree of supercriticality achieved when the chain reaction is initiated. If the neutron background is so large that preinitiation, before the optimal moment, is likely, then the yield varies¹⁸ as (rate of reactivity insertion)^{-1/3}.

Preinitiation reduces yield according to the Poisson statistics of neutron background, and can be counteracted by faster assembly. For a constant level of maximum reactivity insertion, the probability of avoiding preinitiation varies as $1/\exp(\text{neutron source strength} \times \text{assembly time})$.

Preinitiation is a problem faced by any nuclear weapons designer using any fissionable material¹¹. With ²³⁵U (spontaneous fission rate 8×10^{-4} n g⁻¹ s⁻¹), it is a mild problem, so assembly by the relatively slow 'gun' method at published rates < 1 mm μ s⁻¹ (0.3 mm μ s⁻¹ in the Hiroshima bomb) suffices. But even weapons-grade Pu, with neutron background $\geq 60,000$ times higher (just above ²³⁸U), preinitiates unless assembled implisively by a convergent arrangement of chemical high explosives. The radial compression rate can then³² exceed 2 mm μ s⁻¹.

A reflected core of Pu metal, sufficiently subcritical that neutron multiplication can be neglected, will have a neutron background of the order of 0.5×10^6 n s⁻¹ if of weapons grade, several million n s⁻¹ if of reactor grade. The former figure implies a mean time between neutrons of a few microseconds—half an order of magnitude longer than the duration of the fission chain. But the latter figure implies a mean time between neutrons that is short compared with the time required to complete the assembly of a highly supercritical mass, unless that assembly is extremely rapid, implying very high shock velocities and compression. This can in fact be achieved:

"Plutonium of any feasible grade (weapons or reactor) is unsuitable for the gun-assembled systems because the neutron background and relatively long assembly time introduces significant preinitiation probabilities. This is not necessarily true for implosion types"¹⁴.

Preinitiation, then,

"... does not necessarily make an explosive unreliable. Preinitiation *does* result in a statistical uncertainty in the yield ... [that] is statistically distributed between predictable upper and lower limits which are likely to be more than a factor of 10 apart. For a well-understood design properly constructed, however, the most probable yield range could be predicted within much closer limits"¹⁴.

"In implosion devices, preinitiation probabilities may be lowered by various design techniques. Even relatively low

technology designs, notwithstanding the variability in yield, can produce effective, highly powerful weapons"¹⁴.

This can be achieved⁴¹ even with a neutron source strength of the order of 10^6 n s⁻¹. As was officially appreciated in 1944, "... [A] rough quantitative analysis of the assembly velocities attainable with very large charges of high explosive ... suggested that because of the strong focusing effect of the converging material, one could introduce a strong steady source of neutrons into the bomb (for example, by deliberately leaving the material in an impure state), and still beat the chain reaction and attain complete assembly".

Thus preinitiation "... may mean a statistical uncertainty in the yield within a predictable range. Increasing technological sophistication will reduce this uncertainty"¹¹.

Now, consider several levels of "increasing technological sophistication" and their likely effects on the performance of implosion bombs made from reactor-grade Pu or other compositions¹⁷ with high neutron source strength.

Performance as a function of design

Since it became public knowledge that construction of illicit nuclear weapons by non-state adversaries must be taken seriously¹⁹, and that reactor-grade Pu is suitable for such bombs^{17,18,24}, the level of technology on which most discussions have centred can be described as 'crude amateur designs' in which the normal military design requirements for pure fissile material and for the symmetry, simultaneity, and speed of implosion are very considerably relaxed. The canonical description of such designs is that of Willrich and Taylor¹⁹:

"Under conceivable circumstances, a few persons, possibly even one person working alone, who possessed ~10 kg of plutonium oxide and a substantial amount of chemical high explosive could, within several weeks [or perhaps less], design and build a crude fission bomb... [that] would have an excellent chance of exploding, ... probably ... with the power of at least 100 tons of chemical high explosives. This could be done using materials and equipment that could be purchased at a hardware store and from commercial suppliers of scientific equipment for student laboratories. ... [It] might yield as much as 20 kilotons of explosive power—the equal of the Nagasaki A-bomb [though the probability of such a high yield is quite small]."

"... very sophisticated thermal-hydraulic and neutronic calculations"⁴² would not be needed. Several suitably comprehensive literature searches have in fact been conducted by amateurs. The bomb could fit in a car⁴¹.

Making an effective, transportable fission bomb is not a trivial task. Safely realising a paper design in properly working apparatus would require alertness to subtleties and care and skill in technical arts (which many criminal enterprises have shown). The necessary human resources will be assumed here to have been obtained. The skills required for both design and fabrication naturally increase with increasing sophistication and have been taken into account in the policy conclusions drawn here.

Several studies^{12,43,44} have dealt quantitatively with the heterogeneous class of flexible and imprecise designs grouped here as Level One technology. Calculations confirm that in the absence of gross incompetence or malfunction of major components, Level One technology is extremely likely to yield > 0.01 kton, likely to yield in the range 0.1–1 kton, able on occasion to yield several kton, and unlikely to yield 10–20 kton.

A second level of technology might be characterised as 'imitation Trinity designs' or as 1945-vintage US technology. It uses special high-explosive components and detonators (all of which are commercially available in a straightforward geometry to compress an accurately made metallic Pu core. Given the materials and information that have become widely available since the 1940s, such a technology might be typical of a low-level national effort to produce a bomb that can be depended on to work well without previous testing. (It yielded 17 kton.) It is

not a clever technology (simpler means can produce better results) but is basic and reliable, and has been the subject of several amateur design exercises. Five distinguished nuclear weapons experts concluded that using weapons-grade Pu (or ^{235}U or highly enriched ^{235}U)

"... it is possible to design low-technology devices that would reliably produce explosive yields up to the equivalent of 10 or 20 kilotons of TNT. With reactor-grade plutonium it is possible to design low-technology devices with probable yields 3–10 times lower than those mentioned above (depending on the design), but yields in the kiloton range could be accomplished. Militarily useful weapons with reliable nuclear yields in the kiloton range can therefore be constructed using low technology and reactor-grade plutonium"²⁴.

(This is consistent with De Volpi's Table L-6 results¹¹, given realistic choices of parameters.) As for the resources required, "a small group of people, none of whom have ever had access to the classified literature", could get by with "modest machine-shop facilities that could be contracted for without arousing suspicion" and with "a fraction" (perhaps a small fraction) of a million dollars for open-market equipment²⁴.

Recently declassified documents dealing with 1945 US technology give¹

"... quite precise quantitative information ... covering some aspects of how the probability distribution of nuclear yields changes with the isotopic composition of the plutonium used. ... This information makes clear that with power reactor grade plutonium, an implosion weapon of even the simple kind first used by the US would reliably have yields between 1 and 20 kton"²⁵.

Preinitiation at the least favourable moment²⁶ in a Trinity-type bomb would still produce¹ reliable kiloton yields: the worst-case, minimum, 'fizzle' yield is still a "militarily useful"¹¹ ~1 kton. This behaviour is chiefly a function of assembly rate, not neutron background, because the *least favourable moment* cannot get any less favourable. The same conclusion would therefore hold²² even with arbitrarily high neutron source strength, as from 'a large fraction' of ^{242}Pu (ref. 46) and high ^{238}Pu (ref. 37). Contrary to Meyer *et al.*⁴³, "slight mistakes in the knowledge of exact isotopic composition" could not "lead to neutralisation of the explosive design" and could indeed be readily accommodated by design.

Selden summarises¹¹:

"It is likely that a nuclear explosive designer would choose to minimise the ^{240}Pu concentration, given the choice. However, an entirely credible national nuclear explosives capability could be constructed using only reactor grade plutonium."

Of course, the designer may choose to avoid the extra fiscal and political cost (if detected) of the *unambiguously military* dedicated facilities required¹¹ to make large amounts of the more conveniently useable weapons-grade Pu. Some governments may find advantages, notably civilian 'cover', in doing the best they can with their plentiful high-burn-up Pu instead. Recent classified analyses have therefore explored further levels of technological sophistication that can overcome the sub-optimal features of high-burn-up Pu and increase the ~1-kton *minimum* yield of Level Two technology.

Perhaps the most categorical statement of the results comes from a speech¹⁴ by Commissioner Gilinsky (emphasis added):

"... [S]o far as reactor-grade plutonium is concerned, the fact is that it is possible to use this material for nuclear warheads at all levels of technical sophistication. In other words, countries less advanced than the major industrial powers but nevertheless possessing nuclear power programs can make very respectable weapons. And, I might add, these are the very countries whose names turn up in every discussion of proliferation. Of course, when reactor grade plutonium is used there may be a penalty in performance that is considerable or insignificant, depending on the weapon design. But whatever we might once have

thought, we now know that even simple [Level Two] designs, albeit with some uncertainties in yield, can serve as effective, highly powerful weapons—reliably in the kiloton range."

The italicised passages imply that further levels of technology exist with still higher yield and predictability than Level Two.

A third level of technology seeks to overcome preinitiation by extremely rapid assembly. The necessary rates of assembly can be calculated and seem to be readily attainable. One published configuration, for example, is stated to be able to compress a sizeable core at several times the $2\text{ mm } \mu\text{s}^{-1}$ radial rate mentioned earlier. Far higher rates are possible with this method, because in a convergent implosive system, shock pressures vary roughly as the inverse fourth power of radius and shock velocities as the inverse square of radius. Applying the same design to a small core can therefore achieve such high assembly velocities that the shock can traverse much of the core and insert very substantial reactivity before hydrodynamic disassembly forces can dominate. The probability of preinitiation then becomes small, the expected yield relatively large, and its dispersion small: in short, the performance penalty approaches the "insignificant"¹⁴.

Calculations suggest that this Level Three technology is sufficient, using reactor-grade Pu, for almost any military objective, even with attempted 'denaturing'¹⁷. The method will readily occur to most governments and to many technically informed amateurs. The apparatus is not unduly difficult to achieve. It does not necessarily involve a higher technology than Level Two, and should be considered more a logical extension of Level One, a 'smart amateur design', than the exclusive province of governments. It does not necessarily require nuclear testing to ensure confidence in obtaining high yield, provided the maker is confident that the well-characterised non-nuclear components will function as designed. Non-nuclear test firings would, of course, increase this confidence.

Most military bombs are required to function normally in high neutron fluxes such as might arise from nearby nuclear explosions. Essentially the same design considerations apply as in the case of high internal neutron source strengths. It can be safely presumed that these problems are routinely overcome by various means, including thermonuclear techniques that could render the penalty from using reactor-grade Pu not only very small but nil, even at very high yields. This is a very high technology requiring elaborate theoretical, computational, and fabrication facilities, together with prior nuclear testing. But such sophistication is not required for governments or even for some subnational groups to extract from reactor-grade Pu, using Level Three technology, the kind of yield and predictability that the major nuclear powers would have found satisfactory for inclusion in their arsenals around the early 1960s.

Weapons effects and the implications of uncertain yield

Fissioning 1 kg of Pu yields $(2.5 \times 10^{24} \text{ fissions}) \times (\sim 180 \text{ MeV of prompt energy per fission}) = 7.3 \times 10^{11} \text{ J kg}^{-1}$ or $\sim 17 \times 10^{12} \text{ cal kg}^{-1} \equiv 17 \text{ kton kg}^{-1}$. This 17-kton yield (Hiroshima was 13 kton, Nagasaki 22 kton) corresponds to the conversion of a mass defect of only 0.8 g. But unlike chemical high explosives, some of the yield of nuclear explosives appears not as blast or heat but as prompt electromagnetic radiation at many frequencies, especially γ rays, and as prompt neutrons. The smaller the nuclear yield, the more the effects of the nuclear explosion are dominated by prompt radiation.

For example, a 'crude amateur design' yielding only 0.1 kton—which corresponds to fissioning only 6 g (a nominal efficiency of the order of 10^{-3}) and converting a mass defect of 5 mg—typically produces^{19,21} 500 rem of prompt γ dose (roughly the LD₅₀ or dose likely to kill half those exposed to it) at unshielded ranges up to 300 m, plus 500 rem of prompt neutrons ($\sim \text{LD}_{50}$) to ~ 450 m, plus 500 rem of fallout exposure ($\sim \text{LD}_{50}$) to 300–1,000 m for people lingering for an hour. Yet such a surface burst makes a crater only 14 m in radius. Blast

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damage is also of shorter range than the prompt radiation—severe (overpressure to $10 \text{ lb in}^{-2} = 0.68 \text{ bar}$) to 150 m and moderate ($3 \text{ lb in}^{-2} = 0.20 \text{ bar}$) to 300 m. The relatively limited blast damage, even at such low yield, however, could amplify the radiation effects by $\sim 10^3$ times if used to induce a 1% ground release from an operating 1-GWe LWR (16-GCi inventory), ~ 10 –100 times more from a reprocessing plant.

Effects of larger yields are readily, if roughly, calculable from standard scaling laws^{19,53}. For example, a yield of 1 kton, a practical minimum with Level Two technology (but three orders of magnitude larger than a World War II blockbuster), would devastate several km^2 , with 500 rem prompt radiation beyond 700 m and with 500 rem fallout around 1–3 km. If a yield Y expected to be 8 kton is in fact only 1 kton, the blast area will diminish not by 7/8 but by 3/4 (as $Y^{2/3}$), and the lethally irradiated area only by half (as $Y^{1/3}$) (refs 1, 53). Such reductions would generally be smaller than the variability in effect expected from the varying circumstances of use; and except in special tactical-warfare conditions, the important thing is not whether the designer can predict the exact yield, but rather that the potential victim cannot.

Conclusions

The above discussion has sought to provide a discreet, selective, but adequate physical basis for understanding the scope for using reactor-grade Pu in fission bombs at some of the diverse levels of sophistication open to various potential users (the taxonomy given is not exhaustive). 'Denaturing' Pu by adding to it, singly or in combination, essentially inseparable⁵⁴ neutron-emitting diluents such as ^{238}Pu , ^{240}Pu , ^{242}Pu , or ^{252}Cf (ref. 55)—or indeed any other interfering material that cannot be readily removed, for example, by ion exchange—is "fallacious" and "not a valid concept"⁵¹. (Dilution with UO_2 or other materials requiring chemical or physical⁵⁶ separation is a valid concept—it means more material must be diverted and processed^{19,25,34}—but does not solve the problem.) Taking all effects on weapons physics into account, a high ^{238}Pu , ^{240}Pu , ^{242}Pu content may reduce expected yield to a level that could devastate only a modest portion of a city rather than all of it, and may make that yield much less predictable, if the bomb is crudely made. But these faults can be overcome by more clever design, without necessarily using high technology, and at Level Three this can be done by gifted amateurs. It is therefore incorrect to state categorically that bombs made from reactor-grade or deliberately 'denatured'³⁷ Pu are less effective, less powerful, or less reliable than those made from weapons-grade Pu. Whether these reservations hold, and whether by a meaningful margin, depend on the designer's intentions, skills, and resources, all of which may be unknowable. And the implication that the effects of even a

crude, minimal 0.1–1 kton explosion would be tolerable for a free society is at best disingenuous^{19,21,27}.

The foregoing argument also implies that power reactors are not an implausible but are rather potentially a peculiarly convenient type of large-scale military Pu production reactor. This goes beyond the proposition that

"... in situations of extreme tension states may turn to second or third best instruments to get their hands on weapons they regard as essential to their security. The point is that, with plutonium readily available, it may be turned to. And those groups within countries that want to go nuclear can pursue an ambiguous path of keeping their options open until the last minute under a commercial disguise"⁵⁷.

A government can either manipulate civil fuel cycles to produce substantial amounts of low-burn-up plutonium, or, especially using Level Three technology, use high-burn-up Pu in bombs with insignificant performance penalty. Regardless of possible technical measures^{24,25,54,58,59}, such Pu will become readily available in quantities of the order of 10^4 – $10^5 \text{ m}_\text{e} \text{ yr}^{-1}$, and in extracted forms useable for weapons within hours or days, if plans proceed for commercial reprocessing, which is unsafe-guardable both today³⁶ and in principle^{14,59,60}. Making even high-burn-up Pu in domestic power reactors incurs no penalty in reactor efficiency or in equipment costs: a reactor-exporting country will gladly build the reactor, train the technicians, and pay for the whole package with generous export subsidies. If extracted, and using any of the numerous means of evading effective safeguards, the Pu discharged from a single large power reactor suffices for about 10^2 bombs per year, a large weapons programme, and there is the alternative of embezzling up to a few bombs' worth per reactor-year from the fuel cycle within its $\sim 1\%$ statistical 'noise', a form of theft that can be made undetectable in principle. The marginal time and money required to use civil reactors for military production are orders of magnitude less²⁷ than those needed for dedicated military facilities^{11,61}. The extra facilities and staff required could be hidden within the civil programme: the "ideal place to hide a tree is in a forest"⁶¹. And perhaps the greatest attraction of producing military Pu in a power reactor is that it has a civilian 'cover' and thus—at least until regional rivals follow suit—an apparently zero political cost.

In short, the somewhat greater technical difficulty of using power-reactor Pu for effective military bombs—assuming the reactor is actually operated at high fuel burn-up—may be more than counterbalanced by the greater political and economic ease of obtaining that Pu. It "should not be lightly disdained in favour of purer material from dedicated facilities"⁶¹.

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APPENDIX C: THE SEMANTICS OF "DECENTRALIZATION"

So common is the doctrinaire assumption that energy systems must be big in order to be affordable that anyone interested in assessing the merits of energy technologies of appropriate scale is often presumed to be equally doctrinaire in a "small is beautiful" direction. In fact, the late E.F. Schumacher often emphasized that it is just as wrong to be addicted to universally small as to universally large scale: what matters is a scale appropriate for each task. What is appropriate depends not only on economics and logistics (Chapter 5) but also on sociopolitical issues. Those are beyond the scope of this discussion [Lovins 1977] but figure prominently in the wider literature of scale.

Another problem with discussing the full spectrum of technological scale is that to many people, "small" and "decentralized" are interchangeable terms. But the large and growing literature dealing with appropriate technology, alternative development concepts, and "post-industrial" production, settlement, and political patterns is often imprecise in defining "decentralized." The term is in any case, as Langdon Winner remarks, a "linguistic trainwreck"; and besides being oxymoronic, it is ambiguous. To avoid confusion, we confine this discussion to the energy system (not to industrial, urban, or governmental patterns), where we identify eight possible dimensions of "decentralization":

- Unit scale. If "unit" means a device which converts and supplies energy, there is little ambiguity: a unit supplies energy in some form at a rate of so many watts in a particular time pattern, depending on specified parameters. We shall use "scale" in this sense of unit size or output capacity.
- Dispersion. This refers to spatial density--whether individual units are clustered or scattered, concentrated or distributed, relative to each other. It does not specify unit scale or the nature of any interconnections.
- Interconnectedness. Separate units can be coupled to each other, stand-alone (connected only to the end-user), or both optionally. Interconnection may increase reliability, and certainly allows a given amount of supply capacity to meet a somewhat larger amount of diverse demand because not all demands are simultaneous. Interconnectedness says nothing about unit scale, dispersion, or distance from the user. It may refer to electricity or to other forms of energy (e.g. solar collectors connected by a district-heating grid). Interconnections can span a wide range of technical and topological complexity.
- Composition. Different units can be monolithic (consisting of inseparable parts) or modular (combining multiple subunits). A gas-turbine power plant, windfarm, or photovoltaic array is generally modular; a central thermal plant is more monolithic. Proposed "nuclear parks" would be modular but their modules would be individually enormous: composition does not specify unit size.

- Centralization. This is not a technical property of a unit in isolation, but rather expresses its users' perception of its physical and social relationship to them. A centralized unit serves its users via a distribution system which makes the users feel relatively remote, geographically or politically or both, from that unit. A decentralized unit is more local, with short supply lines. A large hydroelectric dam serving several large smelters nearby may seem local and decentralized to their operators; decentralized can be big if the use is correspondingly big. A "windfarm" of many small wind machines at the other end of a long transmission line, or many solar collectors whose heat is distributed via an extensive network institutionally similar to present gas and electric grids, can look centralized to its users; thus a collection of small units can be centralized*. An assemblage of many solar concentrating dishes may be decentralized if dispersed near scattered users, or decentralized if clustered near clustered users. Decentralized does not necessarily mean renewable (cf. dispersed, locally used natural-gas wells or even--in some Swedish proposals--nuclear heat reactors). Conversely, renewable systems can be centralized, as in "power tower," ocean-thermal-electric, biomass-plantation, solar-power-satellite, and similar schemes--although it is not obvious why one should wish to gather up an inherently dispersed energy flux (e.g. sunlight) into one place in order to be put to the expense of distributing it again to dispersed users. Decentralization is a property intermediate between the purely technical qualities described above and the more sociologically oriented ones listed below.

- User-controllability. Many energy users are concerned with the extent to which they can choose and control the energy systems important to their lives. This concern extends both to immediate decisions about end-use patterns--for example, being able to turn a light on and off at one's own convenience preserves individual autonomy--and to the wider question of the political process by which decisions about the energy system are made: whether they are participatory and pluralistic or dominated by a central technical elite.

- Comprehensibility. Whether a technology is arcane or understandable is important to accountability. A system can be understandable to its user even if it is technically very sophisticated. Most people could not build a pocket calculator and do not know exactly what goes on inside it, but for them as users it is a tool rather than a machine: they run it, not the other way around.

- Dependency. The "poles" of this spectrum of economic, political, and psychological relationships might be multinational corporations on the one hand

*In principle, a single small unit could be "centralized away from" its user (note the paradoxical flavor of this phrase) by putting it at the end of a long transmission line, but in practice this would generally be irrational.

and do-it-yourself, appropriate, or (in Ivan Illich's phrase) "vernacular" technologies on the other--things that people can do for themselves. Dependency expresses energy users' feeling that their own interests are not identical with those of energy providers. A high degree of dependency might be characteristic of: a "black box" energy source which is designed, made, and installed by some remote and unaccountable institution; a source which a user is humilatingly unable to understand, repair, adjust, or modify; or a source whose presence or price are beyond users' control. Supplying energy oneself or through more familiar (hence usually more local) institutions would incur a low degree of dependency. Dependency is related also to breadth of choice: buying fuel from one of a number of competitive local distributors offers choice in a narrow sense, but may still create a feeling of dependency if all the fuels are ultimately derived from identical or similar institutions.

The political context in which energy users perceive their supplies might be thought of as a sequence of operations: devices and supplies are produced by an industrial system; a marketing process delivers these outputs to be used by energy conversion systems; these procure and convert energy into useful forms; and an energy distribution system (which could vary in length from inches to halfway around the world) then provides an energy service, generally via an end-use device, to the final user. We are not concerned here with the first two steps in this process (save as their structure contributes to users' perceptions of dependency, controllability, and accountability). The qualities of unit scale, dispersion (density), and composition refer to the energy conversion systems; interconnectedness and comprehensibility refer to those conversion systems and to their associated distribution networks; and decentralization refers to the physical and political relationship of the conversion systems via the distribution networks to the users.

Although we have characterized some of these qualities by their polar extremes, each has a continuum of values in a spectrum. Those values are relative to each other and to a particular context of use. An energy system which is small for running smelters is large for running televisions. One which is distributed across a country may nonetheless be clustered at each point of occurrence. One which is comprehensible to farmers may be mysterious to physicists and vice versa. One which is decentralized in the city may be centralized in the countryside (and possibly vice versa)*. Accordingly, even where a specific meaning can be inferred from context, it is important to remember that all the qualities described are relative, not absolute.

*Recall that in our sense, "decentralized" energy systems are user-centered, i.e. near the user, while "centralized" ones are far away. No wonder these terms have given rise to such confusion!

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The vulnerabilities of the U.S. energy system to accidental or deliberate disruption are analyzed generically and specifically and shown to be disturbingly large. Since they arise from reliance on highly centralized technologies, increasing such reliance is likely to increase national energy vulnerability. A more efficient, diverse, dispersed, renewable energy system is shown to be inherently more resilient, to make major failures impossible, and to be compatible with consistent adherence to free-market principles.

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